Recycling of Deteriorated Asphalt Pavements

by

Kefah Muhammad Abdul-Rahman

A Thesis Presented to the

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In Partial Fulfillment of the
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This thesis, written by Kefah Muhammad Abdul-Rahman under the direction of his Thesis Committee, and approved by all its members, has been presented to and accepted by the Dean, College of Graduate Studies, in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

" الخلاصـــــــــــه "

في معظم البلدان المتقدمه ، أصبحت اعادة استخدام مواد الرصف التالفه اختيار متطور لاصلاح الطرق . لهذا فقد تم اختيار اجزاء تحوي على تكسيرات كبيره ونحت وتفكك في مواد الرصف من طريق الدمام - أبو حدريه السريع كيلو ١٤٠ لدراسة امكانية اعادة استخدامها في هذا البحث . استدعت الدراسة تقييم مخبري لعينات مواد الرصف التالفه وذلك باضافة حصى وزفت حر بالاضافه الى معدل لتصحيح العيوب الموجوده في مواد الرصف التالفه واختيرت خمسة انواع من المعدلات لاعادة حيوية الزفت المعتق نظرا لثبوت صلاحيتها في مثل هذه الحالات وهي موبيل صول ١٢٠ ،ديوتركس ٧٢٩ يوكي الديزل ، الكبريت العنصري ،الكبريت المعدل (اسمنت ٢٠٠٠) ، وقد اسقط الديزل من التجارب التاليه نظرا لخاصية سرعة التبخر والتى ينتج عنها نسبه أعلى فى قساوة الزفت المعدل بالمقارنه للزفت الحر . استخدمت فحوص مارشال لتحديد افضل كميه مقرره من كل من المعدل والزفت الحر اللازم في كل حاله . وأجريت عدة اختبارات ديناميه على قوالب مارشال مثل معامل الرجوعيه ، الشق الكلالي ، والتشوه العمودي الدائم (لتمثيل الاخدود) بطريقة الشد الغير مباشر . واستنتجت قوه الشد الانشطاري تحت تأثير قوه ثابته ، وقد اثبتت التجارب أن خلطه الزفت المدوره تحوي على خصائص تماثل تلك الخصائص التى تحويها الخلطه المكونه من الزفت الحر والتي تعتبر مؤشرا على القوه الكامنه في مواد الرصف المدوره للطرق . ،،،

ABSTRACT

In most of the advanced countries, recycling of deteriorated asphalt pavements has become an established rehabilitation alternative. In this research, failed segment of Dammam-Abu Hadriyah Expressway, which developed high severity alligator cracking, and weathering and raveling at km 140 was selected as a typical candidate pavement to study its adaptability to recycling. The study entailed laboratory evaluation of reclaimed pavement samples with addition of virgin aggregate, virgin asphalt and a modifier to correct the existing deficiencies in the reclaimed pavement. Five types of modifiers, viz. mobilsol 120, dutrex 729 (UK), diesel oil, elemental sulphur, and modified sulphur (Chement 2000), based on their reported proven performance and local availability, were selected to rejuvenate the aged asphalt. Diesel oil had to be dropped subsequently due to its rapid volatilization characteristic resulting in much higher rate of hardening of asphalt blend as compared to virgin asphalt. Marshall mix design tests were conducted to determine the optimum quantity of modifier and virgin asphalt needed in each case. Dynamic tests, in terms of resilient modulus, fatigue cracking and vertical permanent deformation (to simulate rutting), were conducted on Marshall briquettes in an indirect tension mode. Split tensile strength was also determined under static loading. The test results showed that the recycled mixtures possessed characteristics similar to that of the virgin asphalt concrete mixture thus indicating a great potential for pavement recycling in field.

Chapter 1

INTRODUCTION

1.1 General

The Kingdom of Saudi Arabia has about 33,000 km of asphalted roads employing some 10 million tons of asphalt and 5 billion tons of aggregate. These materials can be reused when the pavement wears out. In fact, it was well known in the past that the paving materials were free and reusable; but the technology was not completely refined, and consequently, the materials were usually pushed aside and discarded as rubble and landfills.

The current inflation in cost of construction material as well as shortages of good quality aggregate has led many agencies to evaluate the merits of reusing the distressed asphalt pavements. The process commonly referred to as "recycling", is now well established as a viable technology and is gaining considerable popularity in roadway rehabilitation programs (1, 2, 3, 4). Recycling operation includes breaking up old pavement, reprocessing, and then laying down and recompacting the material. The reprocessing operation includes salvaging the aged asphalt binder by adding a recycling agent, also called modifier or softening agent, that is able to restore the chemical and physical balance of the asphalt binder. It may also include addition of virgin aggregate to correct grading deficiencies in the salvaged pavement. The complete operation is shown schematically in Figure 1.1.

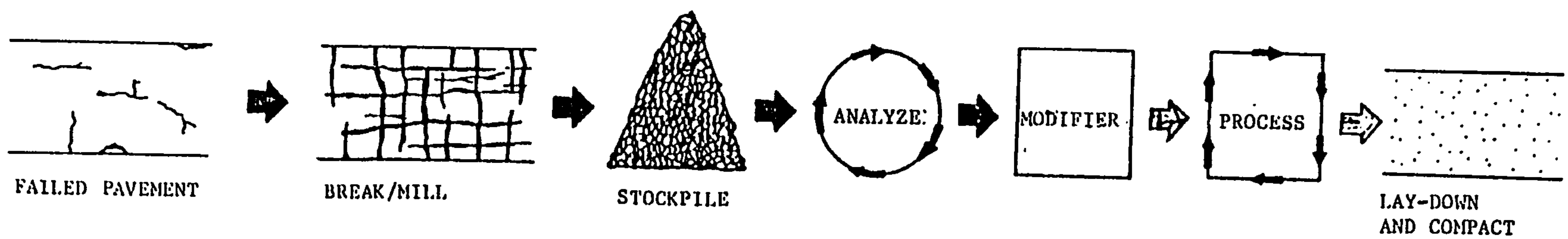

Fig. 1.1 : Schematic of Pavement Recycling Operation (5)

1.2 Recycling as a Rehabilitation Alternative (6)

First step in pavement recycling is to analyze the problem that requires correction. Fig. 1.2 gives a picture of what the engineer is confronted with. First, we need to know why the project study should be undertaken. Is the pavement cracking, raveling, rutting or shoving, and are there other surface or structural deficiencies? Samples may be required of the pavement to ascertain its present condition or quality and determine whether it is deficient in any respect. The original construction records should also be examined to obtain information on specifications, mix design, thickness and materials.

Another question to be considered is adequacy of road geometrics. Past maintenance records should be checked and pavement condition evaluated to determine the possible rehabilitation alternatives.

Finally, the economics of the various choices should be studied. These are the questions that can only be answered through knowledge of current construction and material costs. However, the present trend of increasing energy and asphalt costs makes the recycling process a more viable alternative and also preserves or conserves past investment in highways. For the past thirty years, overlaying an old pavement was a conservation alternative to complete reconstruction process. Now recycling is a conservation alternative to both complete reconstruction or overlaying operations.

1.3 Advantages of Recycling(1,5)

There are several distinct benefits of recycling. Apart from the

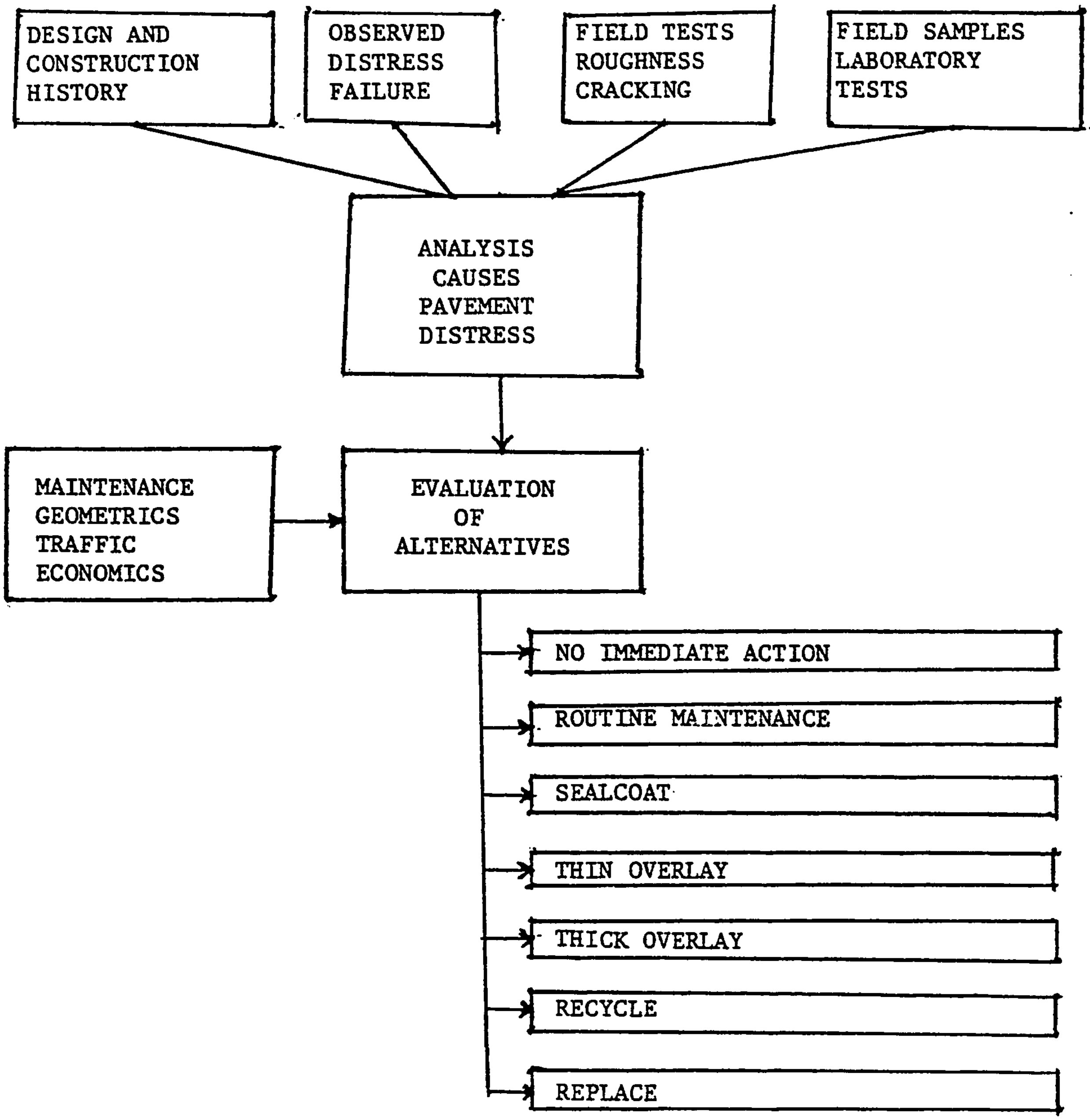

Fig. 1.2: Evaluation of Pavement Rehabilitation Alternatives (6)

economy and conservation of natural resources, recycling provides many other distinct benefits which can be summarized as follows :

(i) Significant structural improvements can be obtained with little or no change in thickness.

(ii) Additional right-of-way is not needed.

(iii) Frost susceptibility may be reduced.

(iv) Surface and base distortion problem can be corrected.

(v) Existing mix deficiencies can be corrected.

(vi) Existing roadway geometry, grades, and alignment can be preserved.

1.4 Scope of the Study

This study was designed to investigate through laboratory tests the recycling potential of a typical failed asphalt pavement in the vicinity of Dhahran-Dammam region. Outer lane of southbound Dammam-Abu Hadriyah Expressway at km 140, which has developed high severity alligator cracking, was selected as a candidate section for investigating its adaptability to hot-mix recycling. This was considered as an excellent candidate for consideration of recycling since it had developed wide cracks ranging from 3 mm to 10 mm and such pavement if overlaid will reflect cracking on the top.

Although routine mix design procedures have been suggested by various agencies, such as the Asphalt Institute (1) and Chevron Inc. (2), for converting the deteriorated pavement into a workable and durable mix, data is lacking for the engineering properties of the recycled materials for predictive performance. Further, recycling potential of deteriorated asphalt pavements has not been investigated so far in the Kingdom of Saudi Arabia. However, with the growing rate of pavement deterioration under escalating traffic loads, the Kingdom has to soon resort to this important technique of pavement rehabilitation. Hot mix recycling technique was adopted here since it is a proven technology suitable for high specification asphalt roads. Keeping in view that no data is available on salvaged pavement material under the operating conditions of the Kingdom, this study was framed with the following specific objectives.

(i) To evaluate through laboratory tests engineering properties of aggregates and asphalt extracted from reclaimed pavement to ascertain their adaptability to recycling.

(ii) To evaluate the properties and effectiveness of selected types of modifiers employed to rejuvenate the aged asphalt. These include dutrex, mobilsol, diesel oil and sulphur (both elemental and modified).

(iii) To design recycled mixtures with each type of modifier and compare their Marshall properties with those of the virgin asphalt concrete mixture.

(iv) To evaluate and compare additional strength properties of the above mixtures, such as resilient modulus and split tensile strength.

(v) To evaluate fatigue cracking and rutting potentials of the above mixtures under repetitive loading, and simulating the inservice operating conditions.

Fullscale field tests will still be required to evaluate the performance of the recycled pavements under actual road conditions. If the results are positive, it will lead to considerable economy and conservation of natural resources.

Chapter 2 provides exhaustive literature review of various techniques of recycling and laboratory procedures recommended for the mix design.

Chapter 3 describes in detail laboratory procedures adopted for design of recycled mixtures using various selected modifiers for softening the aged asphalt.

Various recycled mixtures were further tested for their mechanical properties, such as dynamic resilient modulus and fatigue resistance, under the laboratory repetitive loading system, simulating inservice operating conditions. The test program and the results obtained are detailed in Chapter 4.

Finally, a set of conclusions, and recommendations for future research are drawn in Chapter 5.

Chapter 2

LITERATURE REVIEW

2.1 General

The first mention of recycling dates back to as early as 1915 (7). A number of recycling techniques are said to have been patented during 1930's to 1950's (8). However, the first report on recycling appears in the proceedings of the Association of Asphalt Paving Technologists (AAPT) as late as 1975 (9). In the recent years a large number of reports on pavement recycling are emerging (1, 2, 3).

Several investigations on pavement recycling have been described comprehensively (3), but it will still be worthwhile to review literature applicable to objectives of this study. Information related to field trials and laboratory procedures adopted for mix designs have been reviewed.

2.2 Recycling Alternatives

Categorization of recycling approaches is usually based on the recycling procedure used, the type of paving materials to be recycled and the end products they are expected to produce, or the structural benefit to be gained from the recycling approach. Pavement recycling alternatives have been divided into three general categories (3).

(i) Surface Recycling : It is reworking of the surface of a pavement to a depth of less than about 25 mm (1 in.) by heater-planer, heater-scarifier, hot-milling, cold-planing, or cold-milling devices. This operation is a continuous singlepass, multistep process that may involve use of new materials, including aggregate, modifiers, or mixtures (3).

(ii) In-place Surface and Base Recycling : It deals with in-place pulverization to a depth greater than about 25 mm (1 in.), followed by reshaping and compaction. This operation may be performed with or without the addition of a modifier.

(iii) Central-plant Recycling : This deals with scarification of the pavement material, removal of the pavement from the roadway prior to or after pulverization, processing of material with or without the addition of a stabilizer or modifier, and laydown and compaction to desired grade. This operation may involve additional heat, depending on the type of material recycled and the modifier used.

2.2.1 Surface Recycling

Surface recycling differs from the other broad categories of recycling in that it involves reworking the surface of a pavement to a depth of less than 25 mm (1 in.). Thus, surface recycling has a limited effectiveness in repairing rough riding or severely rutted roads or in significantly increasing the load-carrying capacity of the roadway. However, surface recycling is presently the most popular form of recycling because it can treat a wide variety of pavement distress, including raveling, rutting, flushing, and corrugations at a reasonable cost. Additionally, data illustrate the usefulness of heater scarification plus an overlay to reduce reflection cracking. Other advantages of surface recycling appear to be its ability to promote a bond between the old roadway and a thin overlay and to provide a transition between the new overlay and existing gutters, bridges, pavements, and so forth.

2.2.2 In-Place Surface and Base Recycling

In-place recycling of old asphaltic concrete and portland cement concrete pavement is not a new concept. Almost every state in USA has used conventional construction equipment such as bulldozers, vibratory compactors, rollers, etc. to crush old pavement and combine it with a portion of the existing base or subbase to form a reconstituted structural layer (3). The development of pulverizing equipment and processing techniques are among the most important recent refinements of in-place recycling.

A major advantage of in-place recycling is the ability to significantly improve the load-carrying capability of the pavement without changes in the horizontal and vertical geometry of the roadway. Other advantages include the ability to treat almost all types of pavement distress in asphalt-surface roadways, to reduce or eliminate reflection cracking, and to improve skid resistance and the ride quality of the roadway.

Among the disadvantages are the following : quality control is not as good as that of central-plant operation, pulverization cannot be easily performed on portland cement concrete-surface roadways, proper curing conditions are often required for strength gain, and cost and traffic disruption may be relatively high.

2.2.3 Central - Plant Recycling

Increased interest in central-plant recycling has led to development of new techniques for heating the reused materials and new concepts for pavement removal and sizing.

Two approaches have been used to size the material prior to recycling in a central plant. The pavement can be reduced in size in-place and then hauled to the central plant, or the pavement can be removed from the site and sizing can be performed with equipment normally associated with aggregate processing. In place sizing equipment includes hot- and cold-milling machines, heater-planing equipment, and on-grade pulverizers.

Central plant sizing can be performed with conventional, fixed, and portable crushing and screening equipment. The pavement is normally ripped and broken to a size suitable to be received by the primary crusher prior to loading into the haul units. Jaw and roll crushers have proven to be satisfactory.

Equipment to centrally process recycled material is commercially available and for convenience can be separated into at least four general categories : (i) direct flame heating, (ii) indirect flame heating, (iii) superheated aggregate, and (iv) without heat. Details of the type of equipment presently used can be found in NCHRP (National Council of Highway Research Program) Synthesis of Highway Practice 54 (10).

Major advantages and disadvantages of recycling techniques are summarized in Table 2.1.

2.3 Selection of Recycling Alternatives

If the engineer is to select the most appropriate recycling alternative for a particular project, he must describe or characterize the conditions of the existing facility. The present condition must be measured on some rational basis and compared to standard criteria. Key factors together with a summary of key data describing the existing facility are discussed briefly.

(i) Existing Facility

Particular data are required to describe adequately the existing facility for the purposes of rehabilitation decision-making. Specific items noted are as follows : location and size of project, roadway class, existing pavement cross section, geometrics, traffic, and subgrade characteristics. The contribution of the factors, in terms of a selection process for recycling, are briefly described next.

(ii) Location and Size of Project

The location and size of a project may be such that only certain techniques would be cost effective. For example, projects located in remote areas will have to be large in size to justify the transportation of the equipment associated with central plant recycling. In-place recycling is a cost effective approach for pavement rehabilitation in remote areas where small projects with low traffic volumes are under

Table 2.1 : Major Advantages and Disadvantages of Recycling Alternatives (3)

Recycling Techniques	Advantages	Disadvantages
Surface	- Reduces frequency of reflection cracking - Promotes bond between old pavement and thin overlay and existing gutter, bridge, pavement, etc. that is resistant to ravelling (eliminates feathering) - Reduces localized roughness due to compaction - Treats a variety of types of pavement distress (raveling, flushing, corrugation, rutting, oxidized pavement, faulting) at a reasonable initial cost - Improves skid resistance	- Limited structural improvement - Heater-scarification and heater-planing has limited effectiveness on rough pavement without multiple passes of equipment - Limited repair of severely flushed or unstable pavements - Some air quality problems - Vegetation close to roadway may be damaged - Mixtures with maximum size aggregates greater than 1-inch cannot be treated with some equipment
In-Place	- Significant structural improvements - Treats all types and degrees of pavement distress - Reflection cracking can be eliminated - Frost susceptibility may be improved - Improves skid resistance	- Quality control not as good as central plant - Traffic disruption - Pulverization equipment in need of frequent repair - Pavements cannot be rejected in place
Central	- Significant structural improvements - Treats all types and degrees of pavement distress - Reflection cracking can be eliminated - Improves skid resistance - Frost susceptibility may be improved - Geometrics can be more easily altered	- Increased disruption - Potential air quality problems at plant size - Traffic disruption

consideration.

(iii) Roadway Class

Roadway class dictates criteria for determining the need for pavement rehabilitation as well as general criteria for selection of an appropriate recycling alternative.

(iv) Existing Pavement Cross Section

The date of original construction together with a listing of the thickness and types of materials used will be important in judging the general serviceability of the pavement. Subsequent history of rehabilitation and maintenance activities, such as seal coats, overlays, patching, crack sealing, etc. will influence the determination of a viable recycling alternative. Thickness of each layer of different material, as well as the type of material and its condition, should be obtained from project records. A few carefully located core samples will provide confidence in the information.

The type or nature of the existing material will influence the recycling method selected for a given project. If the bound materials, such as multilayers of seal coats and overlays are variable, both vertically and horizontally, it may be difficult to make a uniform recycled mixture without adding large quantities of aggregate and/or binder to dilute these undesirables. Asphalt modifiers and/or additional asphalt may also be needed. If the structural strength of the pavement must be increased, several options exist that include removing the pavement materials and stabilizing the subgrade before remixing and replacing the pavement, or using all existing pavement materials stabilized as a base course and then overlaying.

(v) *Geometrics*

The geometric features of a roadway, such as horizontal and vertical alignment, are often constraints to conventional rehabilitation techniques such as asphalt overlays. Multiple overlays can cause problems, resulting in excessively high crowns at the centerline and steep cross slopes. Other features such as drainage inlets and manholes also cause problems of a similar nature. Recycling of existing pavement materials offers a solution to some of these problems.

Vertical clearance for trucks and other special vehicles at bridges and overhead signals and signs is often critical and cannot be reduced as would be the case if overlays were used. Recycling offers a further benefit here.

On multilane highways, the truck or travel lane often deteriorates before the passing lane. Overlaying only one of the lanes would be impractical, but recycling of that lane alone or to strengthen it before adding a general overlay would provide a more acceptable solution. Similarly, superelevation could be preserved or altered as needed without disturbing adjacent lanes.

Changing the horizontal alignment or adding new features, such as shoulder widening or a new shoulder, and lane widening or a new lane, may also be opportunities to use recycling techniques. Often, these features may not need the full design strength of adjoining lanes and could be stabilized in-place, or the existing aggregate base could be used to make asphaltic concrete without the need for new materials or for wasting existing materials.

(*vi*) *Traffic Characteristics*

The speed and volume of traffic, to a large extent, determine the traffic control problems associated with pavement rehabilitation activities. The use of recycling on high traffic volume urban facilities should be geared toward those activities that can provide low roadway occupancy time, can be performed with single lane blockage, and can use materials with rapid strength gain after placement.

The volume and axle weight distribution of traffic are important from a pavement design standpoint. For pavement design purposes, traffic should be converted to average daily equivalent 18,000-lb axle-load repetitions that are representative for the design period. It is suggested that the AASHTO procedures be used for this conversion.

(*vii*) *Subgrade Characteristics*

Pavement failures due to factors outside the pavement layers often need to be considered. For example, a subgrade that contains a swelling clay may need to be improved before recycling the pavement materials. Another environmentally influenced problem related to volume change is frost heave. For both of these problems, recycling may offer a reasonable solution in that the pavement materials would need to be removed in any event in order to remove or improve the poor subgrade. While removing the materials, they could be reprocessed and replaced after the subgrade has been prepared.

In summary, all known information about the pavement materials and background needs to be summarized and used in the decision process.

(*viii*) *Surface Condition*

Each potential recycling project should be surveyed for surface defects that can be used not only to assess the cause of distress but perhaps to also suggest correct action. Several agencies have devised methods to estimate pavement distress and one such approach is the paver technique (11). Some methods of recycling would not be particularly beneficial for certain types of distress. For example, a pavement with severe alligator cracking over 30 percent of the area would not be improved by using a heater planer alone. Similarly, other surface methods would not be applicable unless a thick overlay followed the operation.

(*ix*) *Structural Condition*

The structural adequacy or structural condition of the roadway under consideration is determined by the thickness of the overlay required. Overlay requirements should be determined by an appropriate deflection-based procedure. Certain recycling alternatives defined in this report can be eliminated, depending on the thickness of the overlay required. For example, if the overlay required is greater than 51 mm (2 in.), only those recycling alternatives providing a major structural improvement would be considered adequate. For overlay requirements less than 51 mm (2 in.) those recycling alternatives providing minor structural improvements are suggested for use.

(x) Roughness

The smoothness of ride may be a deciding factor for rehabilitation of any roadway. Occasionally, a rough surface may be the only significant problem and surface recycling would be the solution. If a pavement is rough, but also has other deficiencies that require more extensive reworking, the roughness should be taken care of automatically in that operation. For example, it is not recommended that very rough primary highway (PSI less than 2.4) be surface recycled without an appropriate overlay.

(xi) Skid Resistance

Many pavements may perform adequately from a structural standpoint, but simply be deficient in skid resistance because of excess asphalt cement or perhaps because of polishing aggregate. As part of the overall pavement testing scheme, skid resistance can be measured by using any one of several test methods, but preferably by the so-called ASTM skid trailer. it is noted that all recycling methods are appropriate for improving skid resistance with the possible exception of the heater planer without additional aggregate (17) or heater scarifier only (19).

2.4 Recycling Modifiers

Asphalt binders present in recycling pavements often have physical or chemical properties that make the "old" asphalt undesirable for reuse without modification.

As an asphalt pavement ages, significant changes take place in the pavement components. Asphalt hardens and loses ductility as it ages in the pavement. The viscosity of the asphalt increases and the penetration drops. Ductility also decreases on aging.

Asphalt aging in pavements results from several causes as explained below :

(i) Absorption by the aggregate - The lighter oil fractions of the asphalt are absorbed into the pores of the aggregate particles. The amount of absorption is variable, depending on the nature of the aggregate. This absorption not only reduces the effective binder content, but also results in apparent "hardening" of the asphalt because of the selective absorption of the lighter fractions of the asphalt cement.

(ii) Oxidation volatilization, other chemical changes - These processes, which occur gradually during the life of the asphalt in pavement service, cause the proportion of the various asphalt components to change. Typical of the change is the data developed from the Michigan Test Road after 18 years of service as shown in Fig. 2.1 (2). The relative loss of the lower molecular weight fractions of the asphalt cement, and a corresponding increase in the proportion of the asphaltenes, result in

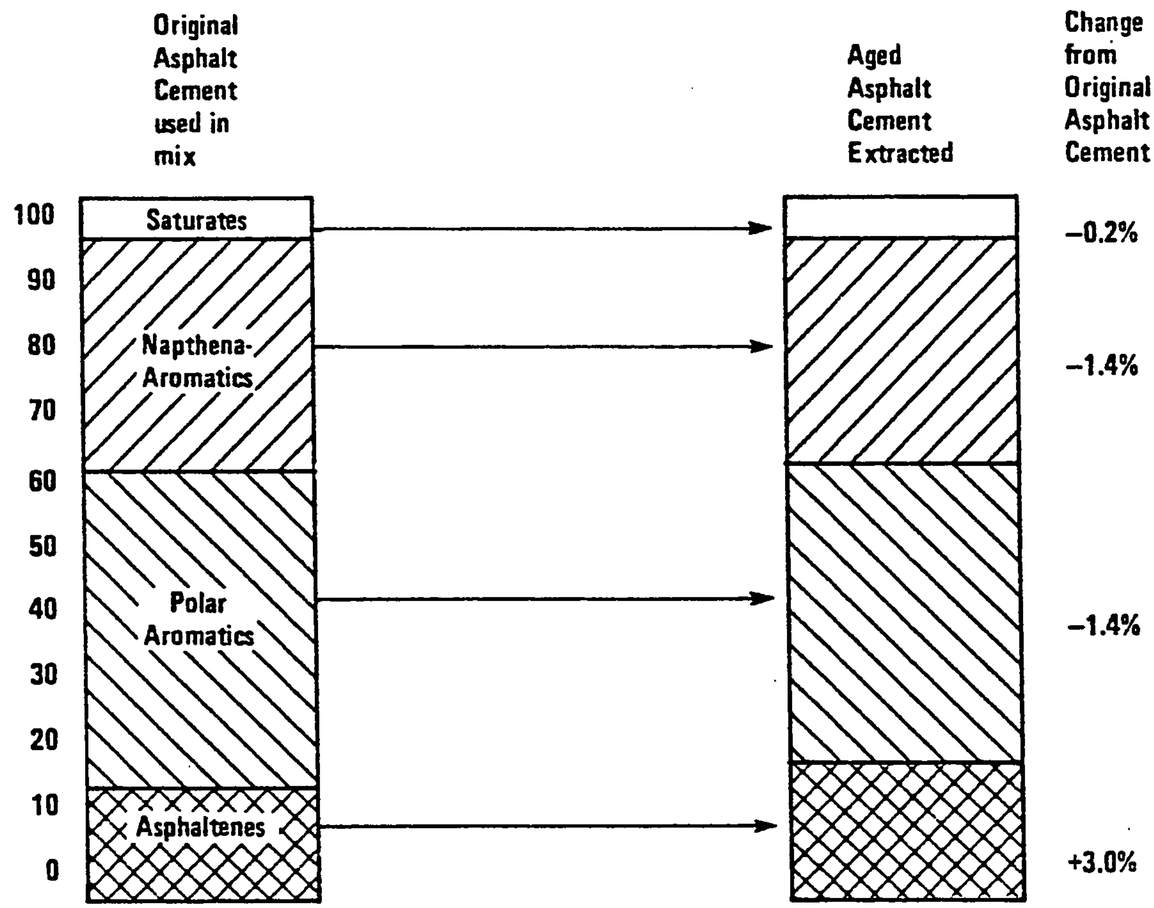

Fig. 2.1 : Changes in Asphalt Composition with Hot Mixing and Pavement Aging (2)

the hardening and loss of ductility of the binder. To reconstitute the aged asphalt, it is necessary to replace all the lost components.

Materials have been developed to restore these old binders to a condition suitable for reuse. This concept is not new and has been the subject of a number of studies during the last several years.

Materials used to alter properties of asphalt cements are called softening agents, reclaiming agents, modifiers, recycling agents, fluxing oils, extender oils, or aromatic oils.

The term "modifier" will be used to designate this type of material in this report and originates from ASTM Subcommittee D4.37 (Modifier Agents for Bitumen in Pavements and Paving Mixtures). The general definition of a modifier is "a material when added to asphalt cement will alter the physical-chemical properties of the resulting binder" (3). A more specific definition has been developed by the Pacific Coast User-Producer Group for the term "recycling agent" (13). A recycling agent is a hydrocarbon product with physical characteristics selected to restore aged asphalt to requirements of current asphalt specifications. It should be noted that soft asphalt cements, as well as specialty products can be classified as recycling modifiers or agents.

The purpose of the modifier in asphalt pavement recycling is to (3) :

(i) Restore the recycled or "old" asphalt characteristics to a consistency level appropriate for construction purposes and for the end use of the mixture.

(ii) Restore the recycled asphalt to its optimal chemical characteristics for durability.

(iii) Provide sufficient additional binder to coat any new aggregate that is added to the recycled mixing.

(iv) Provide sufficient additional binder to satisfy mixture design requirements.

2.4.1 Properties of Modifiers

Modifier properties of interest to the engineer are those that can be used for specification purposes to ensure that the modifier will perform the following functions :

(i) Be easy to disperse in recycled mixture (13, 16).

(ii) Alter viscosity of old recycled asphalt cement to the desired level (13, 14, 15,16).

(iii) Be compatible with the old recycled asphalt to ensure that syneresis (exudation of paraffins from asphalts) will not occur (13, 14).

(iv) Have the ability to disperse the asphaltenes in the old recycled asphalt (15).

(v) Improve the life expectancy of the recycled asphalt mixture (13, 14, 15, 16).

(vi) Be uniform in properties from batch to batch (15).

(vii) Be resistant to smoking and flashing if used in hot mix operations (13, 14, 15, 16).

Tests that have been investigated by various groups for inclusion in specifications are as follows :

(i) Viscosity at 38, 60, 99, 135°C (100, 140, 210, 275°F), ASTM D2170, D2171.

(ii) Flash point, ASTM D92.

(iii) Volatility, ASTM D1160.

(iv) RTF-C residue (weight loss, viscosity change, ductility, penetration), AASHTO T240.

(v) Rostler parameters (compatibility, chemical composition), ASTM D2006.

(vi) Clay-gel absorption chromatograph, ASTM D2007.

(vii) Mixed analine point.

(viii) Refractive index.

(ix) Fire point.

(x) Smoke point.

(xi) Solubility parameter.

(xii) Specific gravity, ASTM D70.

(xiii) Viscosity-gravity constant.

(xiv) Spot test.

A review of the references cited indicates that materials of a wide range of viscosity, as well as other properties, are available. For example, the viscosity as measured at 60C (140F) ranges from 0.0024 to 64 Pa.s (2.4 to 64,000 centistokes, flash points range from 88 to 384°C or 190 to 658°F), asphaltenes content ranges from a trace amount to 51 percent, nitrogen bases range from 1.2 to 41.2 percent, paraffins range from 0.2 to 43.5 percent, and specific gravity ranges from 0.891 to 1.148.

2.4.2 Blends of Modifiers and Aged Asphalts

It is sometimes assumed that the field mixing process together with a reaction time (of unknown length) will allow the modifier and the old recycled asphalt to be completely mixed. If this supposition is accepted, the problem of blending old asphalts and modifiers is greatly simplified. The basic laboratory steps consist of extraction and recovery of the old asphalt followed by mixing various percentages of modifier until the desired consistency is obtained. This process is basically a trial and error procedure; however, methods of predicting modifier contents to produce desired viscosities have been developed and published by Chevron (16), Dunning (15), Pacific Coast User Producer Group (13), and Witco (14). The basis for all of these methods is basically the same in that the viscosity of a blend of asphalts of different viscosity can be characterized by equations of the following form (13, 14, 15, 16).

$$\log (v) = a + bp \qquad \text{Eq. 2.1}$$

$$\log - \log (v) = a + bp \qquad \text{Eq. 2.2}$$

$$\log - \log (v) = a + b (\log p) \qquad \text{Eq. 2.3}$$

where v is the viscosity of the blend (normally measured at 140°F (60°C) in centistokes, p is the volume percent modifier in the blend, and a and b are constants. If no modifier is used, the viscosity is that of the old asphalt. If 100 percent modifier is used, the viscosity is that of the modifier. Hence, the constants a and b must be determined for each old asphalt-modifier blend. Typical blending chart produced by Chevron (2, 16) is shown in Fig. 2.2.

Two grades of modifier (recycling agent) are shown. Each agent softens the aged asphalt. However, the amount required varies. In the example shown, 41 percent of the low viscosity material is required in the final binder, while 64 percent of the high viscosity agent would be required to produce a desired 1,000 poises asphalt viscosity at 140°F. For a typical aged mix with 5 percent asphalt, about 2.1 percent of the low viscosity material would be needed (i.e. 0.05 x 41) while 3.2 percent (i.e. 0.05 x 64) of the high viscosity recycling agent would be required. From these data it appears more economical to use the low viscosity material.

The aged asphalt in combination with the agent must also satisfy the desired asphalt specifications. In the example given (Fig. 2.2), the low viscosity material when blended with the aged asphalt, failed to meet ductility requirements. The reconstituted asphalt also aged rapidly and was not equivalent to new asphalt.

Experience has shown that higher viscosity recycling agents are more effective. They contain the necessary blend of components required to replace those normally lost in weathering. This will help raise the quality level of the aged asphalt in the RAP to that of virgin asphalt. In the example given the low viscosity agent is not effective in restoring many aged asphalts recovered from pavements.

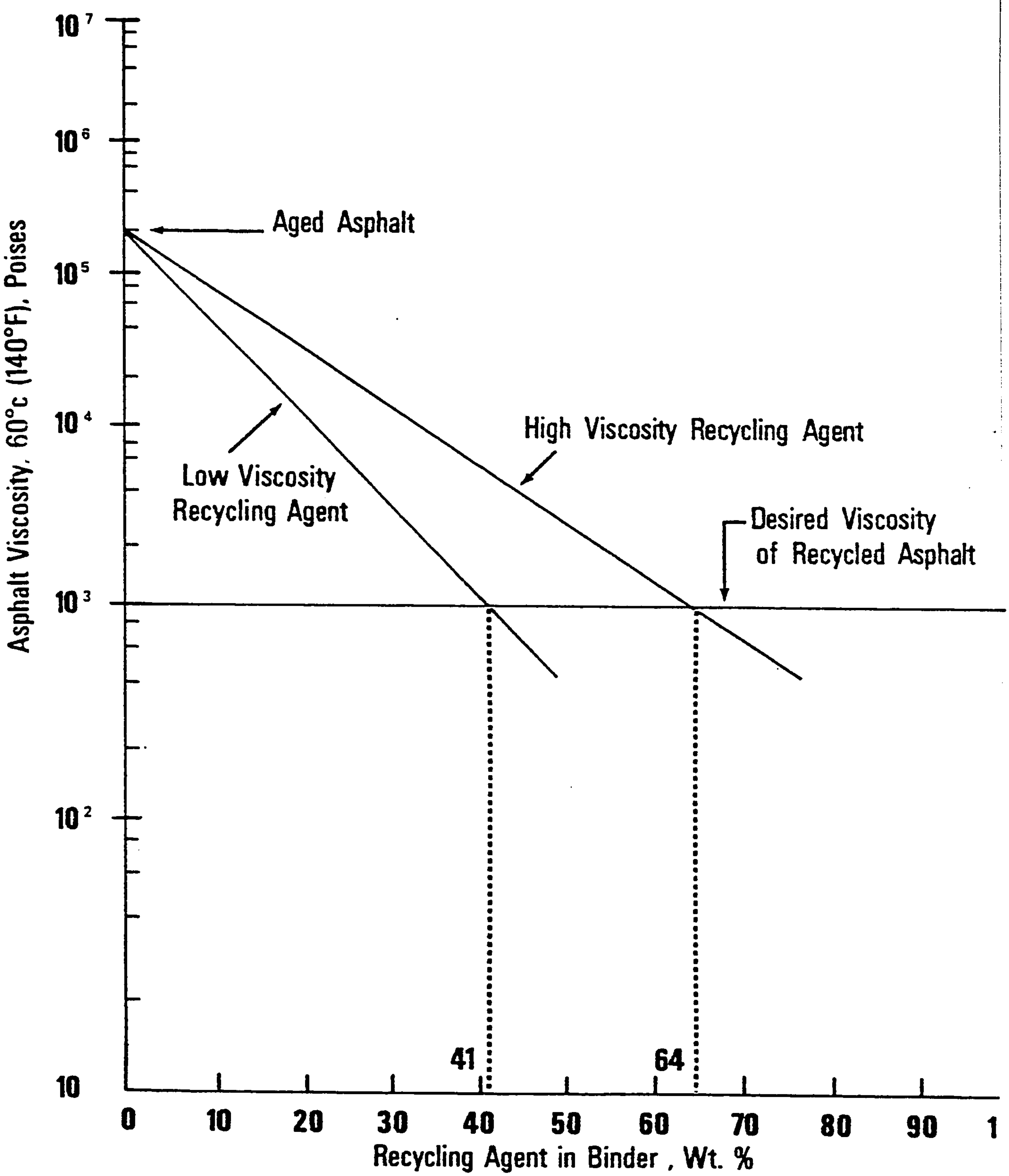

Fig. 2.2 : Percent Recycling Agent Required Depends on Viscosity (2)

2.5 Laboratory Mixture Design

The recycling of old bituminous-bound pavements often requires special consideration because the binder is often hard and brittle. Asphalt modifiers can be used to soften these old binders and produce mixtures with properties similar to those of conventional asphalt-bound materials. The method outlined in the following is recommended by Epps et al. (3) after that suggested in Davidson et al. (17), Dunning (18), Canessa (19), and Terrel et al. (20). It consists of the following general steps. (i) evaluation of salvaged materials, (ii) determination of the need for additional aggregates, (iii) selection of modifier type and amount, (iv) preparation and testing of mixtures, and (v) selection of optimum combinations of new aggregates and asphalt modifiers. These are discussed below in detail.

(i) Acquisition of Field Samples

Representative field samples should be obtained from the pavement to be recycled. A visual evaluation of the pavement should be made together with a review of construction and maintenance records to determine significant differences in the material to be recycled along the pavement section. Roadway sections with significant differences in materials should not be lumped together because uniformity and predictability of results will be impaired. Locations within a project can be determined on a random basis using the procedure outlined in the Asphalt Institute Manual Series 17 (21). At least 5 or 6 locations should be used as a minimum, and a total composite sample of about 890

N (200 lb) is recommended for laboratory evaluation. If desired, core samples may also be obtained and used for comparison of original and recycled properties such as stability and resilient modulus (22).

(ii) Extract and Recover Asphalt and Aggregate

Extraction and recovery tests should be performed at each location sampled. Results of these tests (penetration, viscosity, asphalt content) together with thickness measurements made from the cores should help determine the uniformity of the section under consideration for recycling. Sufficient asphalt should be recovered to permit blending with asphalt modifiers for further testing.

(iii) Aggregate Properties

Aggregate recovered from the samples in step (ii) should be tested for gradation and durability, such as Los Angeles Abrasion and Polish value, if the recycled mixture is to be used as a surface course. These data can be used to establish project uniformity together with the recovered asphalt data obtained in step (ii).

(iv) New Aggregate

New aggregate may have to be added to the mixture for one or more of the following purposes : (a) satisfy gradation requirements; (b) skid resistance requirements for surface courses; (c) air quality problems associated with hot, central plant recycling; (d) thickness requirements; and (e) improved stability, durability, flexibility, etc.

Gradation requirements for recycled mixtures should be those presently required by the specifying agency or those in ASTM D3515.

To provide initial and long lasting skid resistance for the recycled bituminous surface course, it may be necessary to blend coarse nonpolishing aggregate with the recycled pavement. It appears that 40 percent by volume of the plus No. 4 fraction should be nonpolishing to provide the desired skid performance on moderate- to-high traffic volume facilities(3).

Air quality regulations for hot, central plant operations necessitate the use of a minimum of about 30 to 40 percent by volume of new aggregate. This requirement will be gradually reduced as equipment manufacturers and contractors improve the hot recycling operation(2).

Replacing the recycled pavement with a thicker section of asphalt stabilized material may be required from a structural pavement design standpoint. This can be accomplished by blending new aggregate with the recycled material or by the additional layers of new asphalt stabilized materials. If hot, central plant operations are to be used, it appears practical to blend the new aggregate with the recycled pavement.

(v) *Asphalt Demand*

The asphalt demand of the proposed recycled material can be estimated from the following (3).

$$D_T = V_R D_R + V_N D_N \qquad \text{Eq. 2.4}$$

$$D_R = D_{CKE} - A_R \qquad \text{Eq. 2.5}$$

in which :

D_R = asphalt demand for salvaged or recycled aggregate, percent.

D_{CKE} = CKE derived oil ratios for salvaged or recycled aggregate, percent;

A_R = asphalt content of salvaged or recycled aggregate;

V_R = volume of recycled aggregate in mixtures;

V_N = volume of new aggregate in mixtures; and

D_N = CKE derived oil ratios for new aggregate, percent

It should be noted that if new aggregate is not used, Eq. (2.4) becomes Eq. (2.5).

The asphalt demand determined in this manner should be considered as an estimate and can be used as a starting point for mixture design purposes.

(vi) Asphalt Properties

Asphalt recovered from the samples in step (ii) should be tested for penetration at 25°C (77°F) and viscosity at 60°C (140°F). Asphalt content, penetration, and viscosity should be determined on all extracted samples. These data can be used to determine project uniformity.

(vii) Determine Type and Amount of Modifiers

The type and amount of modifiers can be selected by using Fig. 2.3 and Table 2.2 together with a definition of the penetration or preferable viscosity of the binder in the processed recycled mixture and a

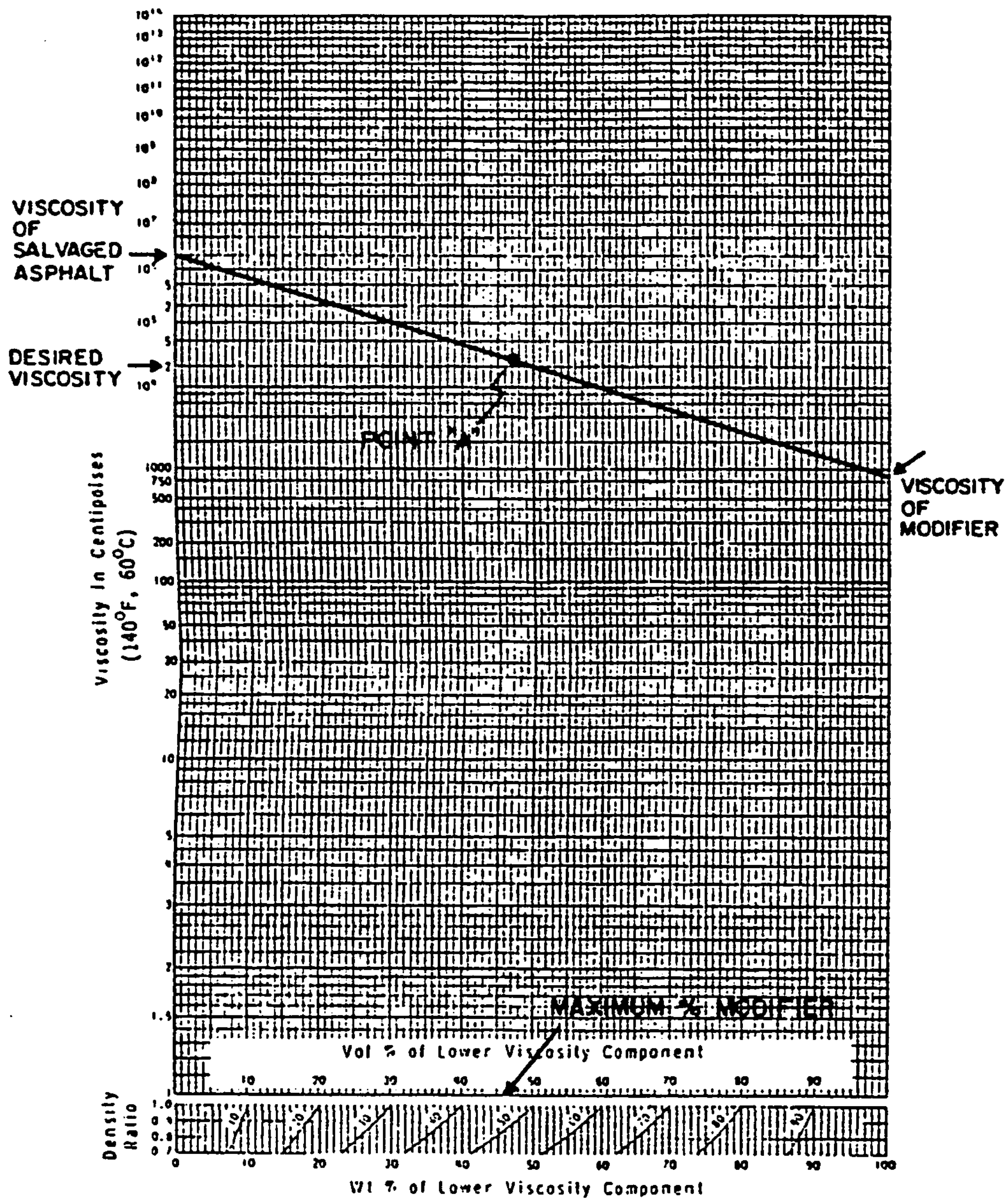

Fig. 2.3 : Viscosity Blending Chart (13)

Table 2.2 : Proposed Specifications for Hot Mix Recycling Agents (3)

Test	ASTM Test Method	RA 5 Min.	RA 5 Max.	RA 25 Min.	RA 25 Max.	RA 75 Min.	RA 75 Max.	RA 250 Min.	RA 250 Max.	RA 500 Min.	RA 500 Max.
Viscosity @140°F cSt	D2170 or 2171	200	800	1000	4000	5000	10000	15000	35000	40000	60000
Flash Point COC,°F	D92	400	-	425	-	450	-	450	-	450	-
Saturates, wt.%	D2007	-	30	-	30	-	30	-	30	-	30
Residue from RTF-C Oven Test @325°F	D2872										
Viscosity Ratio	-	-	3	-	3	-	3	-	3	-	3
RTF-C Oven Weight Change, ±, %	D2872	-	4	-	4	-	2	-	2	-	2
Specific Gravity	D70 or D1298	Report		Report		Report		Report		Report	

knowledge of the asphalt demand of the recycled mixture which was obtained in Eq. 2.4. For example, assume the following (3) :

1. CKE oil ratios on extracted salvaged or recycled aggregate, D_{CKE} = 5.0 percent.
2. Percent asphalt in salvaged or recycled material, A_R = 4.0 percent.
3. Viscosity of aged asphalt = 20,000 poises.
4. Additional new aggregate, V_N = 30 percent.
5. CKE oil ratio of new aggregate, D_N = 6.0 percent.
6. Desired viscosity of recycled asphalt = 2,000 poises.

From Eqs. 2.4 and 2.5, the following asphalt demand can be calculated :

$$D_T = V_R D_R + V_N D_N$$

$$D_R = D_{CKE} - A_R$$

$$D_R = 5.0 - 4.0 = 1.0$$

$$D_T = (0.70)(1.0) + (0.30)(6.0)$$

$$D_T = 2.5 \text{ percent}$$

The maximum percent modifier by weight of total binder in the recycled mixture is therefore :

$$[D_T / (V_R A_R + D_T)] \times 100$$

$= [2.5 / ((0.70 \times 4.0)+ 2.5)] \times 100 = 47$ percent

The Fig. 2.3 is entered with the volume percent of lower viscosity modifier (47 percent) and the desired viscosity of the recycled binder to locate point A. Point A is connected with the viscosity of the recovered salvaged binder and the line projected to obtain the viscosity of the modifier. Table 2.2 indicates that modifier grade RA-5 would likely be suitable.

(viii) Modifier Tests

Sample of modifiers to be used on the job should be obtained and subjected to tests to establish their conformance to specifications (Table 2.2) as well as to establish the viscosity of the modifier in order to obtain a more realistic modifier content (Fig. 2.3). A partial list of modifier suppliers is given in Table 2.3.

(ix) Blend Modifier with Recovered Asphalt

The modifier that may consist of an asphalt cement and softener should be blended with the recovered asphalt and subjected to viscosity and penetration tests to determine if the predicted viscosity (penetration) of the blend was accurate. It is suggested that two blends, one 5 percent above and one 5 percent below the precent recycling agent determined in step vii be made. About 75 to 100 grams of recovered asphalt for each blend should be used. A third blend may be required to confirm the desired viscosity or penetration.

Some recycling modifiers may not be compatible with the salvaged

Table 2.3 : Partial List of Modifiers for Recycling Asphalt-Aggregate Mixtures(3)

Supplier	Product Name or Identification	History of Laboratory Study	Use Field Study
Arizona Refining Co.		x	
	Light Aromatic Oil	x	
Ashland Petroleum	Medium Aromatic Oil	x	
Company	Slurry Oil	x	
	Ashland Plasticizer Oil (APO)	x	x
Bituminous Materials Company, Inc.		x	
Cenex	Dust Oil	x	
Chem-Crete Corp.		x	
Chevron USA, Inc.	Chevron X109	x	
	Chevron X90	x	
Mike Davis Associates		x	
Koppers Co., Inc.	BPR	x	x
Lion Oil Co.	Smackover Flux Asphalt	x	
	Rejuvenator Oil	x	
Mac Millan		x	
Mobil Oil Corp.	XMTY-1258	x	
	Mobilsol 30	x	
Pax International	Paxole	x	x
	Petroset	x	
Phillips Petroleum	10 Extract	x	
Company	20 Extract	x	
	250 Extract	x	
Saunders Petroleum Company	SA-1	x	x
Shell Oil Co.	Dutrex	x	x
Sun Oil Co.	Sundex 840T	x	
	Sundex 790T	x	
Tenneco		x	
Union Oil Co.	Rejuv-Acota-Base	x	
Witco Chemical	Reclamite	x	x
	Cyclogen	x	x
	Cutback Asphalt		x
	Emulsified Asphalt	x	x
	Califlux GP	x	
Numerous Companies	Soft Asphalt Cement	x	x
	Reclaimed Oil	x	

asphalt. Therefore, a thin-film oven test should be performed on the selected recovered salvaged asphalt-modifier blend. A ratio of the aged viscosity to original viscosity of less than 3 will indicate that the recycling agent is likely to be compatible with the recovered salvaged asphalt.

(x) Preliminary Mixtures

Five different mixtures of recycled aggregate, new aggregate if desired, and modifier should be fabricated. Three samples of each mixture should be fabricated and subjected to stability testing and tests to determine the air void content. These preliminary tests should vary the percent new asphalt cement and/or the type and amount of modifiers. It is helpful to have an experienced engineer present during the mixing and molding operation because subsequent trial mixtures may depend on the appearance of the first few trial mixtures. It should be realized that the modifiers often have a delayed softening reaction.

(xi) Detailed Mixture Evaluations

The three most promising mixtures evaluated in step (x) should be evaluated in detail for properties that can be used in pavement thickness design and for durability considerations such as water susceptibility. The amount of testing will depend on the capability of the agency considering the recycling project.

(xii) Select Optimum Mixture Design

The optimum mixture design should be based on results of steps

(x) and (xi) and economic and energy considerations. Reference 23 can be used as a general guide.

The foregoing discussion is primarily directed toward the use of hot, central plant operations which is the type of recycling technique under study in this research.

2.6 Field Reports on Recycling

During the past few years, there has been increasing interest across the U.S. in recycling of old asphalt-pavements and road bases. The reasons behind it are the soaring costs of asphalts, aggregates, energy and labor at a time when road maintenance budget are being squeezed. Some of the field projects undertaken are described below.

Wisconsin DOT (Department of Transportation) did some recycling test projects(4). In the first project, the job was to rehabilitate a 20-mile stretch of road. That road had up to 7 in. of asphaltic concrete pavement laid over an old concrete pavement. Wisconsin used a milling (grinding) machine to remove the asphalt pavement. The material was collected, dumped in trucks, transported to a distant batch-type hot-mix plant, and the resulting hot-mix recycled material, with fresh quantities of aggregate and asphalt added, placed on the same roadway.

Wisconsin's second experimental project involved the repair of a 4.6-mile stretch of road, a rural state highway, consisting of a 2 in. thick asphalt pavement over a gravel road base. A ripper mounted behind a tractor was used to break up the pavement, and the pieces were placed into trucks using a front-end loader. These were then transported to a modified drum-mixer-type hot-mix plant, where virgin materials were added to the salvaged pavement to form a recycled mix. The plant operated cleanly - without any air pollution.

Wisconsin strongly favors hot-mix recycling over cold recycling. This is because in cold recycling there is less control on mix design and aggregate gradation. It is also difficult to get perfect mixing or a perfectly homogeneous mix. The old asphalt and the new asphalt do not have a chance to melt and flow together. The cold mix recycled pavement is, therefore, not as strong as a hot-mix recycled pavement (4). Encouraged by the success of its demonstration projects, the state is now going ahead full speed with hot-mix recycling. In 1980 alone, it worked on over 30 hot-mix recycling jobs - more than half of all the pavement rehabilitation work being done by the state (4).

According to Wisconsin DOT's Chief Design Engineer David Strand (4), hot-mix recycling, is clearly a way to stretch the dollar. For instance, in 1980, the average cost of repairing a road in Wisconsin using virgin bituminous pavement was 16.85 dollars/ton of pavement placed. That includes all cost - preparing the road, materials, mixing, laying down, etc. By contrast, the total cost of repairing a road there via the hot-mix recycling approach was 10.62 dollars/ton - a saving of 40 percent. As contractors get more experience and are able to write off the cost of equipment modifications, those prices will drop still further.

In the past few years, many Wisconsin asphaltic-concrete contractors have purchased new drum mixer plants equipped with the modifications needed for handling recycled pavement. Drum mixers are a favorite among contractors. One reason is that they can make up asphaltic concrete hot mix using up to 70 percent recycled pavement. By contrast, a batch plant uses a maximum of 50 percent recycled materials, the remainder being new aggregate and new asphalt.

Wisconsin has also used sulphur as a substitute for asphalt on one hot-mix recycling job (4). Normally, some new asphalt must be added to the recycled pavement during the hot mix operation. But instead of adding pure asphalt, Wisconsin engineers are now adding a blend of asphalt and sulphur. To date, engineers have used sulphur blended with asphalt in virgin mixes on an experimental basis. Wisconsin is believed to be the first group to try the use of sulphur in a hot mix using recycled pavement materials. According to Strand (4) adding a sulphur-asphalt mix to a recycled mix in a hot-mix plant worked well. During the hot-mix operation, Wisconsin adds a 70 percent virgin asphalt - 30 percent sulphur mixture to the process. Meanwhile, the Southwest Research Institute (San Antonio, Texas) has been developing a method for using all sulphur (Sulphlex) as the binder in pavements. Results reported to be encouraging. In summing up, Strand (4) hopes that the Wisconsin DOT can use sulphur in the future to replace much of the virgin asphalt that would otherwise be used in recycled pavements, and to replace all of the asphalt used in virgin mixes for entirely new pavements.

Whitcomb et al (24, 25) reported the first hot-mix asphalt recycling project in Oregon. It was decided to recycle 45,000 metric tons of asphalt concrete pavement placed for rehabilitation of interstate highway I-5. The extracted asphalt showed an absolute viscosity of 7000 and 7700 poises, and a penetration of 46 and 50. The Oregon mix design procedure (a modified Hveem Method) was used to determine the optimum asphalt content and the difference between the optimum content and the asphalt content of the original mixture was satisfied with addition of AR-2000. Also 0 to 20 percent of aggregate was added.

A report by Takeuchi (26) is probably the first to describe the recycling of asphalt pavement in Japan. No information is available about the old asphalt properties. The pavement was 5 years old, and repair was required due to heavy damage in the subgrade caused by seepage of water. Usually this type of repair is done by replacement with new pavement materials, but since excavated pavement materials have been designated an industrial waste by law, dumping these materials was restricted and estimated hauling costs were very high. This situation led to the reuse of the old materials as part of the asphalt treated base course material. About 10 percent of the old material by the weight of the total mixture was mixed with the new mixture using a "sandwich" technique, in which the old materials in layers were placed between layers of the new hot mixture in hauling truck. Heat was expected to penetrate into the old materials and a great success was reported.

Chapter 3

RECYCLED MIXTURE DESIGN

3.1 Introduction

This chapter details the laboratory procedure actually adopted for designing the recycled mixtures using certain selected types of modifiers, viz. mobilsol 120, dutrex 729 (UK), commercial grade diesel oil, and sulphur, both elemental and modified (Chement 2000). Hot-mix recycling was adopted since it is considered to yield homogenous mix of properties comparable to virgin hot-mix asphaltic concrete for high-specification asphalt roads (4). Failed segment of southbound Dammam-Abu Hadriyah expressway at km 140 was selected as a candidate section for recycling.

The laboratory mix design included evaluation of engineering properties of pavement component materials viz. asphalt and aggregate from the failed pavement segment and the additions of virgin aggregate, virgin asphalt and a modifier needed to improve the mix deficiencies. Marshall mix design procedure as recommended by the Asphalt Institute (1) for hot-mix recycling was adopted. For sulphur addition, the procedure recommended by U.S. Bureau of Mines (27) was adopted with certain modifications as necessary in terms of mixing process for recycling. Prior to accepting the hydrocarbon based modifiers for use in recycling operation, the aging characteristics of their blends with recovered asphalt were investigated to ensure their long term effectiveness. These aspects and the test results are discussed in this chapter in the subsequent sections. The sequence of testing is shown schematically by a flow diagram in Figure 3.1.

3.2 History of Candidate Pavement for Recycling

As mentioned earlier, southbound Dammam Abu-Hadriyah Expressway at km 140, which was opened to traffic in 1980, was selected as a candidate pavement section to investigate the recycling potential of typically failed pavement sections in the Kingdom. The outerlane of this expressway has shown signs of premature failure in terms of high severity alligator cracking, 3 mm to 10 mm wide. Close-up view of pavement condition is shown in Fig. 3.2. This segment of the road has been carrying excessively heavy loads, mostly of trucks carrying sand and aggregates from local crushers(28). The cracking could also be attributed to high ground water table due to irrigation fields on either side. The ground water table was found to be only about 1.10 m (43.3 in) below the pavement surface. The pavement was also characterized by high Benkelman beam deflection of the order of 1.42 mm (0.056 in.), indicating the need of a very thick overlay of about 203 mm (8 in.) (28). Even this may not ensure long term good performance, since the chances are that the existing wide cracks may propagate upwards eventually and reflect on the top of the overlay. Complete reconstruction could be a viable alternative; but hot-mix recycling may be a more promising alternative, since apart from being economical, it will solve the problem of reflection cracking and will also provide an opportunity

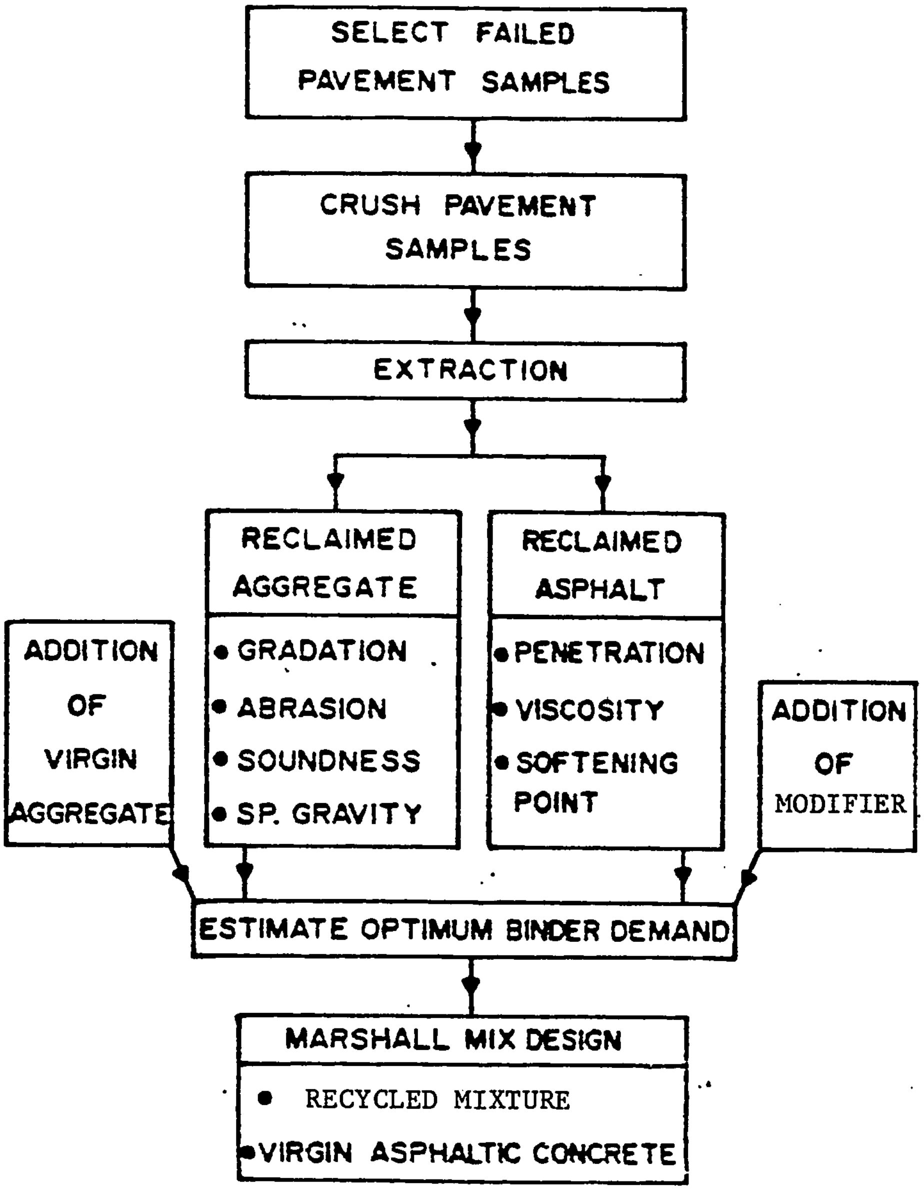

Fig. 3.1 : Flow Diagram of Testing Sequence for Laboratory Mix Design

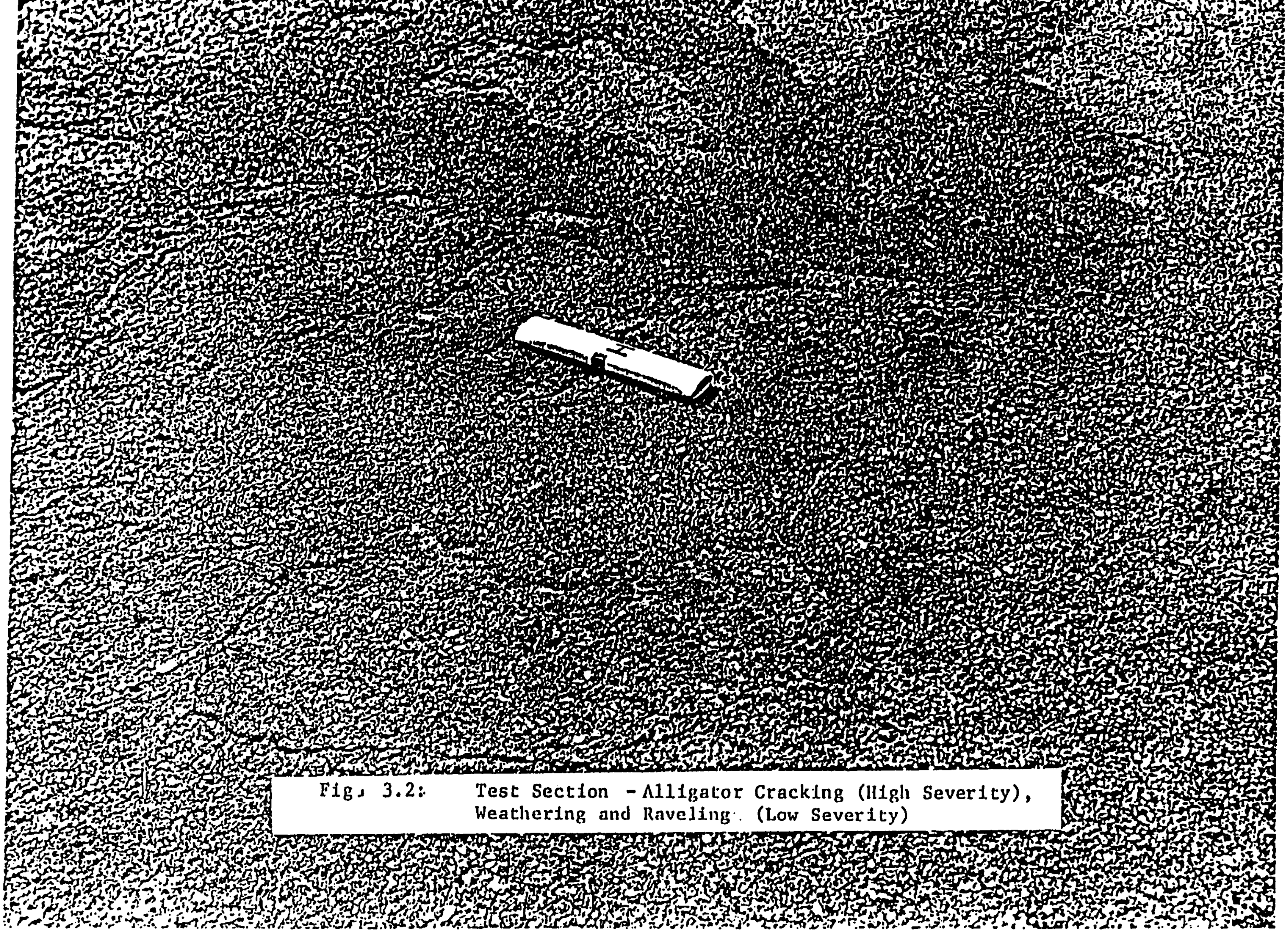

Fig. 3.2: Test Section - Alligator Cracking (High Severity), Weathering and Raveling. (Low Severity)

to correct the suspected drainage problem at the subgrade level.

The pavement cross-section with layer thicknesses is shown in Fig. 3.3 The road was opened to traffic in 1980. The current status of this section is that certain portion of the segment showing wide spread alligator cracking is being repaired by full depth patching. While this work was in operation, lumps of ripped pavement, each weighing about 311 N (70 lbs) were selected on random basis for laboratory evaluation for hot-mix recycling.

3.3 Preliminary Assumptions for Field Sampling

With the decision to recycle the failed segment of Dammam-Abu Hadriyah expressway, the existing pavement had to be tested for recycling compatibility. This required certain preliminary assumptions to be formulated prior to mix design so that field samples collected for laboratory evaluation are representative of the pavement to be recycled. These assumptions were as follows :

(i) Central plant hot-mix recycling technique will be used since this technique is more advanced and suitable for the existing conditions.

(ii) Recycling process for each asphaltic concrete layer viz. wearing course and base course, will be carried out separately.

(iii) The pavement is ripped using normal ripping machine.

(iv) The reclaimed asphalt pavement (RAP) will be further reduced in size to a limit where the individual pieces of pavement will disintegrate to the original aggregate sizes during the mixing cycle.

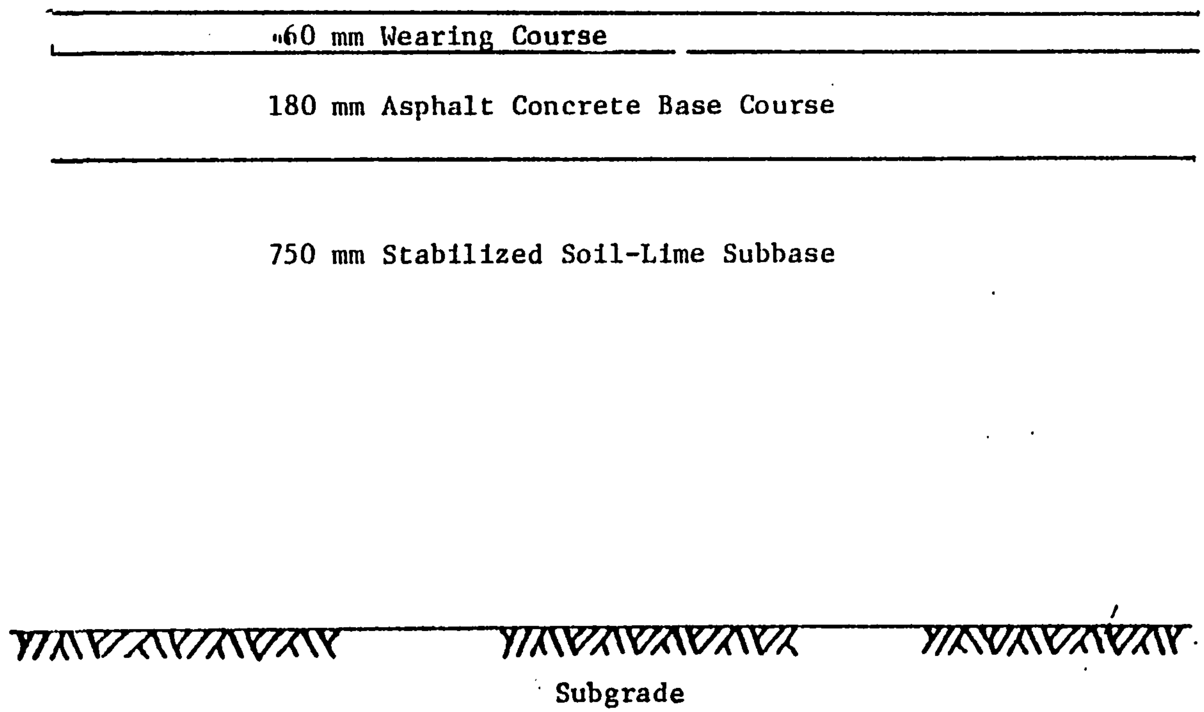

Fig. 3.3 : Pavement Cross-Section Showing Layer Thicknesses of Dammam-Abu-Hadriyah Expressway

Chevron (2) recommends this limit for batch plant mixing to be all passing 50.8 mm (2 in.) or 63.5 mm (2.5 in.) screen.

(v) Crushing of RAP will be performed in a normal jaw and roll crushers to the size mentioned in (iv) above.

(vi) Additional virgin aggregate, if needed to correct the grading deficiencies of the crushed pavement, will be provided from the selected nearby quarry.

(vii) Suitable modifier will be added, if needed, to rejuvenate the recovered asphalt.

3.4 Crushing of Field Samples

Pavement lumps from ripped segment of Dammam-Abu Hadriyah expressway were collected on random basis and further sawed to a manageable size and weight (about 311 N, 70 lbs). About 50 such pieces were brought in the laboratory for recycling study. The wearing course layer was separated from the base course by simple chiselling. Since the objective of this study was to investigate the recycling potential of a typical failed asphaltic concrete pavement in the Kingdom, this study was confined to wearing course layer only. The base course layer, being less exposed to solar radiation and load stresses, will undergo less severe distresses and will be more easily adaptable to recycling. The pavement lumps from the wearing course layer were hauled to a nearby crusher when they were crushed to minus 50.8 mm (2 in.) size as required for batch plant feeding. The average gradation of crushed pavement samples is presented in Table 3.1. Subseq-

Table 3.1 : Average Gradation of Failed Pavement Samples After Crushing

Sieve Size	2 in.	1 in.	1/2 in.	No.4	No.40	No.80	No.200
Percent Retained	0	18.6	38.1	23.7	16.7	1.4	0.9
Percent Passing	100	81.4	43.3	19.6	2.9	1.5	0.6

uent testing was conducted on these crushed pavement samples which are representative of the field samples under real life situation.

3.5 Evaluation of Reclaimed Aggregate and Asphalt

The next step in the testing sequence, as shown in Fig. 3.1, is to run extraction tests, ASTM-D2172, on crushed pavement samples with a view to obtain informations on properties of reclaimed aggregates and asphalt. Asphalt was recovered from the asphalt-solvent (trichloro) mixture by the Abson method ASTM-D1856. The recovered asphalt was tested for penetration at 25°C (77°F) using ASTM D5-73 and for absolute viscosity at 60°C (140°F) using ASTM D2171.

3.5.1 Aggregate Gradation

The test results for aggregate gradation are presented in Table 3.2. The aggregate grading requirements for wearing course, as per the Ministry of Communications (30), are also included in Table 3.2 to provide a direct comparison with the grading of the reclaimed aggregates. The two grading data are also plotted in Fig. 3.4. It is observed from the above table and the figure that the reclaimed aggregate had larger percentage of finer fractions which may be attributed to inservice degradation in addition to pavement ripping and subsequent crushing. It, therefore, required blending with coarser fractions from 19.05 mm (3/4 in.) and 12.7 mm ($\frac{1}{2}$ in.) stockpiles of virgin aggregates to meet the specification limits.

Practical considerations on plant operations limit the reclaimed

Table 3.2 : Gradation of Reclaimed Aggregate from Extraction Tests

Sieve Size mm(in.)	Percent Passing Sieve Size Shown #1	#2	#3	#4	#5	#6	Range	Average	Ministry's Require-ments
19.0 (¾)	100	100	100	100	100	100	100	100	100
12.7 (½)	99.6	99.6	99.5	99.2	99.6	99.5	99.2-99.6	99.5	80-100
4.75 (0.187)	72.6	73.2	74.4	75.4	74.1	73.8	72.6-75.4	73.9	50- 70
2.00 (0.0787)	51.0	52.9	54.5	55.1	53.1	53.7	51.0-55.1	53.4	32- 47
0.425 (0.0165)	29.7	31.8	33.0	33.2	31.2	32.6	29.7-33.2	31.9	16- 26
0.180 (0.0070)	18.5	20.6	21.9	21.1	19.0	18.9	18.5-21.9	20.0	10- 18
0.075 (0.0029)	9.6	9.5	9.8	10.1	9.6	9.8	9.5-10.1	9.7	4- 10

asphalt pavement proportions to about 35 to 65 percent with the remainder being virgin aggregate (2). Virgin aggregate used in this study was derived from the conventional sources of limestone normally used in hot mix paving specifications for primary highways in the vicinity. Reclaimed/virgin aggregate blend of 50/50 was selected. The following basic formula of Asphalt Institute (29) was used for blending with coarser fractions from 19.05 mm (3/4 in.) and 12.7 mm (½ in.) stockpiles.

$$P = Aa + Bb + Cc \qquad \text{Eq. 3.1}$$

where

P = the percentage of material passing a given sieve for the combined aggregates A, B, C, etc.;

A,B,C, etc. = percentage of material passing a given sieve for aggregates A, B, C, etc.; and

a, b, c, etc. = proportions of aggregates, A, B, C, etc. used in the combination and where the total = 1.00.

It yielded design grading satisfying the Ministry's specifications for wearing course as shown in Tables 3.3 and 3.4. and in Fig. 3.4.

3.5.2 Other Physical Properties of Aggregates

Reclaimed aggregate as well as the virgin aggregate were subjected to further testing to investigate other physical properties which are of significance for asphalt hot-mix construction. These included Los Angeles abrasion tests, soundness test, water absorption test and

Table 3.3 : Typical Grading of Various Stockpiles Available at the Crusher Site

Sieve Size mm (in.)	Percent Passing Sieve Shown 19 mm* (3/4 in.)	12.7mm* (1/2 in.)	Sand	Filler
19.0 (3/4)	100	-	-	-
12.7 (1/2)	19	100	-	-
4.75 (0.187)	12.7	46.1	-	100
2.00 (0.0787)	4.76	9.1	100	85.2
0.425 (0.0165)	1.48	9.0	67.5	25.5
0.180 (0.0070)	0.37	2.7	34.6	19.5
0.075 (0.0029)	0.18	2.2	4.9	12.4

* Used for blending with reclaimed aggregate

Table 3.4 : Final Design Grading Obtained for Mix Design

Reclaimed Aggregate	Final Gradation	Ministry's Specifications
100	100	100
99.5	86.3	80-100
73.9	60.5	50- 70
53.4	35.3	32- 47
31.9	22.5	16- 26
20.0	14.4	10- 18
9.7	6.2	4- 10

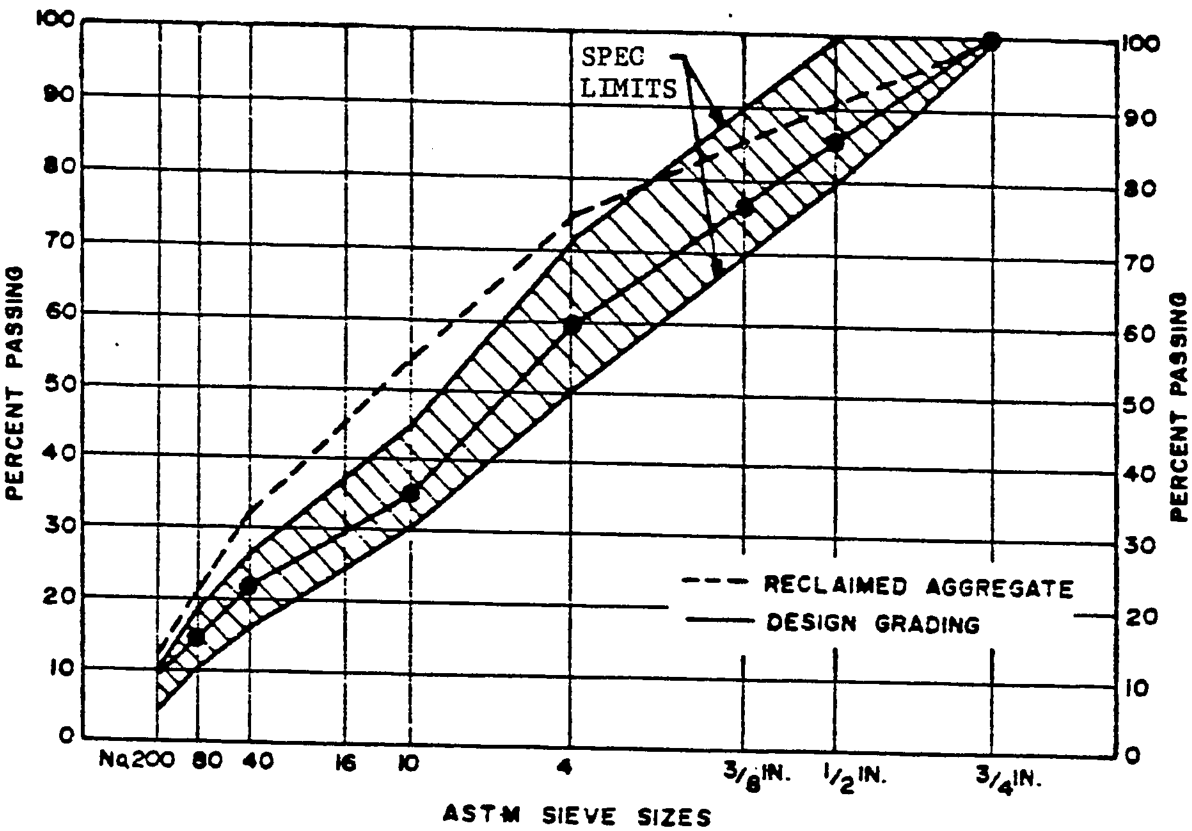

Fig. 3.4 : Grading of Reclaimed Aggregate and Final Design Grading

specific gravity test.

The test results together with the specifications from the Ministry of Communications (30) and ASTM (31) are summarized in Table 3.5. Both the reclaimed aggregate as well as the virgin aggregate are found to meet the Ministry's as well as ASTM specification limits for hot-mix for wearing course, except for the soundness test in which case the Ministry's limits are lower than the ASTM and found to be not satisfying the observed values. Both the reclaimed as well as the virgin aggregates are found to show higher loss in soundness test than the limits recommended by the Ministry of Communications. However, they both satisfy the limits set by the ASTM.

3.5.3 Physical Properties of Asphalt

Table 3.6 summarizes results of asphalt content as determined from the extraction tests. It shows average asphalt content of 5.8 percent with standard deviation of 0.052 percent. It yielded mean penetration value of 25 and mean viscosity value of 20,180 poises at 60°C (140°F). Comparison with virgin asphalt properties, shown in Table 3.7, indicates considerable aging of asphalt in RAP. This clearly indicates the need of a modifier to improve the rheological characteristics of the aged asphalt.

3.6 Selection of Modifiers

3.6.1 Modifier Types

A modifier was needed to soften the aged asphalt in RAP as

Table 3.5 : Properties of Extracted and Virgin Aggregates

Properties	Test Results		Specified Values	
	Extracted Aggregates	Virgin Aggregates	ASTM	Ministry of Communications
Loss Angeles Abrasion % Loss				
- Coarse Aggregate	-	19.8%	40% Max	40% Max
- Fine Aggregate	-	42.5%	-	-
Soundness Using Magnesium Sulphate, % Loss				
- Coarse Aggregate	15.9%	10.8%	18% Max	12% Max
- Fine Aggregate	16.0%	17.3%	20% Max	
Water Absorption				
- Coarse Aggregate	1.918%	1.921%	-	-
Specific Gravity	2.566	2.556	-	-

Table 3.6 : Reclaimed Asphalt Content from Extraction Tests

Test Number	Asphalt Content % by Total Mix
1	5.8
2	5.8
3	5.9
4	5.8
5	5.9
6	5.8

Average Asphalt Content = 5.8 %

Standard Deviation = 0.052 %

Table 3.7 : Properties of Virgin and Reclaimed Asphalt

(A) Virgin Asphalt

Penetration, ASTM D5-73 - 55

Absolute Viscosity at 60°C, ASTM 2171 - 2630 Poises

(B) Reclaimed Asphalt

Penetration, ASTM D5-73 - 25

Absolute Viscosity at 60°C, ASTM 2171 - 20,180 Poises discussed in the section 3.5.3 above. Selection of the modifier was based on the availability of suitable type in the Kingdom. Three types of hydrocarbon based modifiers viz. mobilsol 120, dutrex 729 (UK) and commercial grade diesel oil were obtained from the local suppliers. Both mobilsol 120 and dutrex 729 (UK) are essentially aromatic oils with high flash point. They showed excellent compatibility with asphalt as detected by visual inspection of the blend through a microscope. Their properties are summarized in Tables 3.8 and 3.9, respectively.

Diesel oil which is normally used to flux asphalt to soften it was also included as per recommendations of various agencies (3).

Sulphur, both elemental and modified (Chement 2000) of commercial grade, were also used both as a modifier as well as a partial replacement of virgin asphalt addition. This technique was tried in USA, in laboratory as well as fullscale application in field, and found to yield satisfactory results (4, 27, 32). Use of sulphur for recycling asphalt pavements is also described in Reference 5. Physical properties of sulphur used as determined in the laboratory here are summarized in Table 3.10.

3.6.2 Modifier Percentage

(i) Mobilsol and Dutrex

For mobilsol and dutrex, the quantity of modifier to be added was fixed from the consideration of softening the extracted asphalt to a target value of the viscosity equal to that of the virgin binder. Modifier in the range of 8 to 14 percent by weight of the blend was added to

Table 3.8 : Properties of Mobilsol 120 Used as a Modifier for Recycling*

Property	Description
Oil Type	Aromatic
API** Gravity	10
Pour Point °C	26.7
Flash Point °C	254.4
SUS*** 98.9°C	105.0
Colour	Dark
Aniline Point°C	40.6

* As provided by Supplier, Haji Abdullah Alireza, Oil Division

** API : American Petroleum Institute

*** SUS : Saybolt Universal, Seconds

Table 3.9 : Properties of Dutrex 729 (UK) Used as a Modifier for Recycling*

Property	Description
Type	Aromatic
Density at 150°C	1.00
Pour Point °C	3.00
Flash Point (COC) °C	210
Kinematic Viscosity 40°C	552 cst
Kinematic Viscosity 100°C	15 cst
Refractive Index 20°C	1.583
Aniline Point °C	23
Viscosity Gravity Const.	0.97

* As provided by the supplier, Abdul-Aziz & Mohamed Al Jomaih Oils & Tyres Division

Table 3.10: Properties of Sulphur Used

(A) Elemental Sulphur

Specific gravity = 1.96

*Viscosity at 125°C = 0.1 poises

(B) Modified Sulphur

Specific gravity = 1.91

*Viscosity at 125°C = 0.3 poises

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*Determined by cone and plate viscometer the aged asphalt and the viscosity of the blend was determined at 60°C using ASTM D2171. The results are plotted in Figs. 3.5 and 3.6 which indicate required percentage of mobilsol and dutrex as 11 percent and 12 percent, respectively, by weight of total blend with aged asphalt.

It may be pointed out that the aged asphalt needed for blending was prepared by weathering the asphalt artificially in oven. The study made by Escobar and Davidson (33) showed interesting results by comparing the field data with three ways of accelerated aging, and concluded that the hardening of asphalts by prolonged exposure in the RTFC oven and mild air blowing are reasonable approaches to simulate severe field hardening of asphalts. Based on their results, it was decided that heating of asphalt in a thin film in an oven should be employed in this study to achieve same level of hardening in virgin asphalt as obtained in actual field. ASTM D1754-78, Standard Test Method for Effect of Heat and Air on Asphaltic Materials (Thin-Film Oven Test), specifies that 50 ml of asphalt be exposed to heat at 162.8°C (325°F) for 5 hours. Since the level of consistency of asphalt to be recycled was determined to have viscosity of 20180 poises, the time period necessary to attain this level should be determined. To do this, eight samples of virgin asphalt, each in a pan, 140.2 mm (5.5 in.) in inside diameter and 9.5 mm (3/8 in.) deep, were prepared and put into the oven at 162.8°C (325°F) with air circulated. The pans were not rotated but placed on a shelf in the oven. After predetermined time periods, each sample was poured into a 3 oz. can and cooled to the room temperature. The viscosity values were measured at 60°C (140°F)

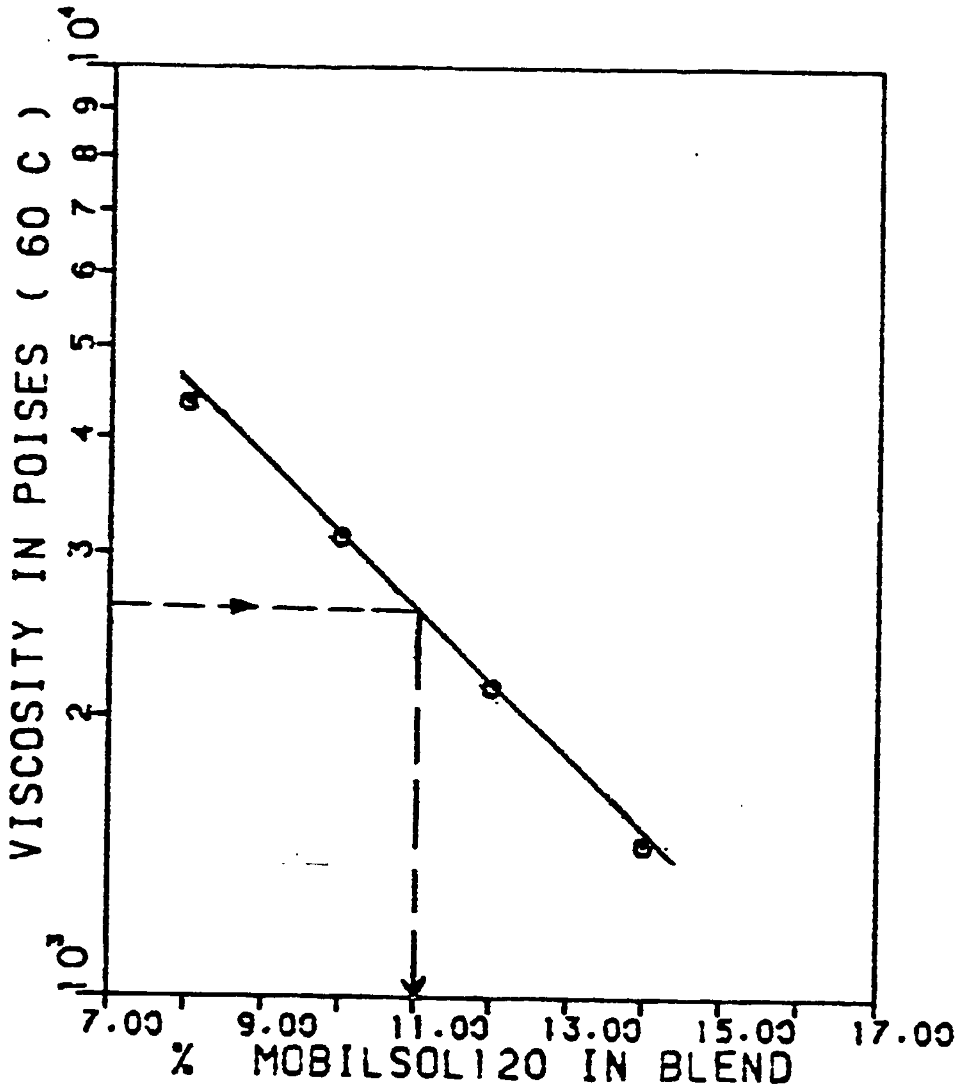


Fig. 3.5 : Effect of Mobilsol Percent on Blend Viscosity with Aged Asphalt

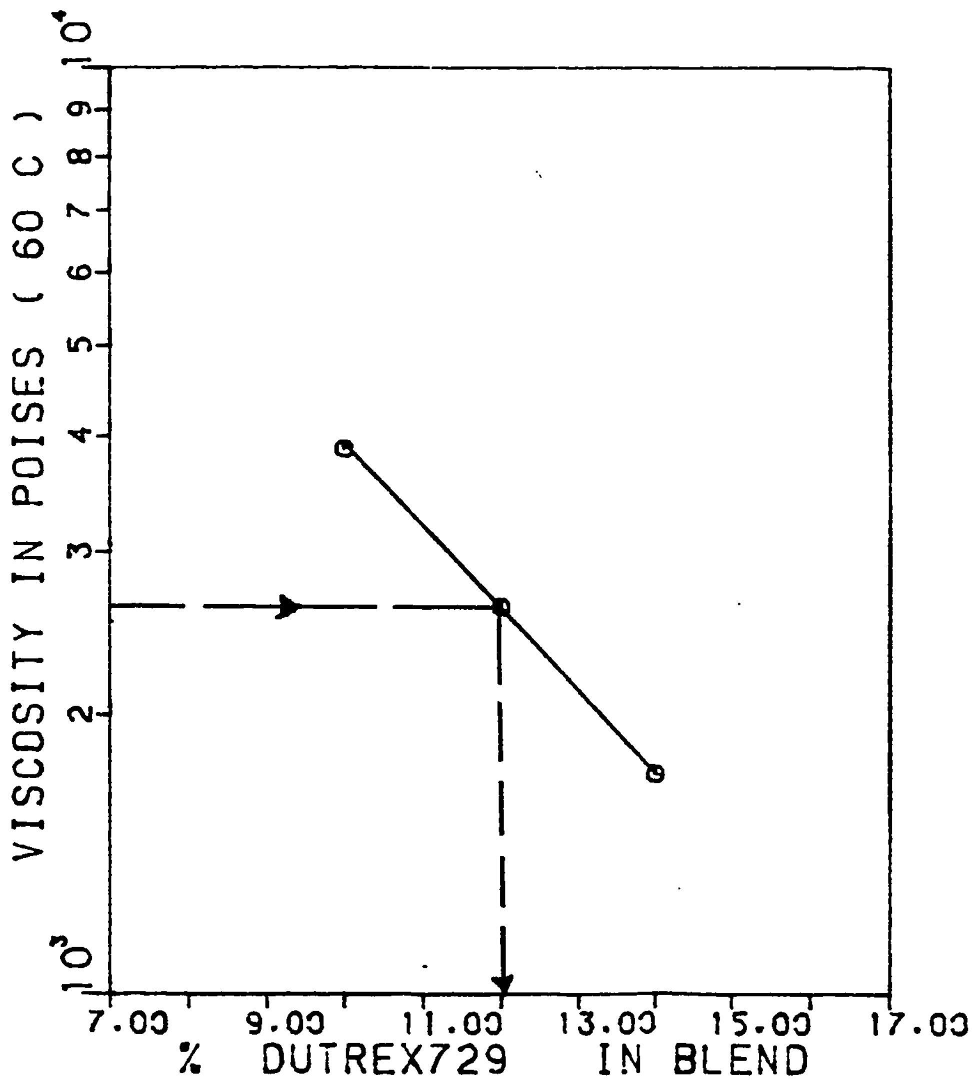


Fig. 3.6 : Effect of Dutrex Percent on Blend Viscosity with Aged Asphalt

according to ASTM D2171. The results are shown in Fig. 3.7. From the results obtained above, it was decided that heating for 12 hours was appropriate to achieve a viscosity value of 20,180 poises.

(ii) Diesel Oil

The diesel oil of commercial grade was blended with virgin asphalt. The blending percentage was controlled from the requirement of flash point temperature of the blend, which should be well above the maximum temperature to which the binder will be heated in the hot-mix plant. The flash point temperature of the virgin asphalt-diesel blend (liquid asphalt) decreased with increasing diesel percentage as summarized in Table 3.11. Diesel oil, 4 percent by weight of the liquid asphalt was selected as the maximum quantity that could be used, keeping the flash point temperature within the acceptable limit. Its viscosity at 60°C (140°F) was determind by ASTM D2171 and found to be 610.4 poises. Fig. 3.8 shows blending of aged asphalt with liquid asphalt to achieve the target viscosity of 2600 poises, requiring 52 percent of liquid asphalt in the blend.

(iii) Sulphur, Elemental and modified

Previous research with sulphur-asphalt binder (SA), has shown that sulphur additions reduce the viscosity of asphalt in the heated or hot-mix state and might well do the same to the viscosity of asphalt in the heated asphalt in recycled pavements and thus prove to be a good softening agent. Table 3.12 (34, 35) shows the physical properties of

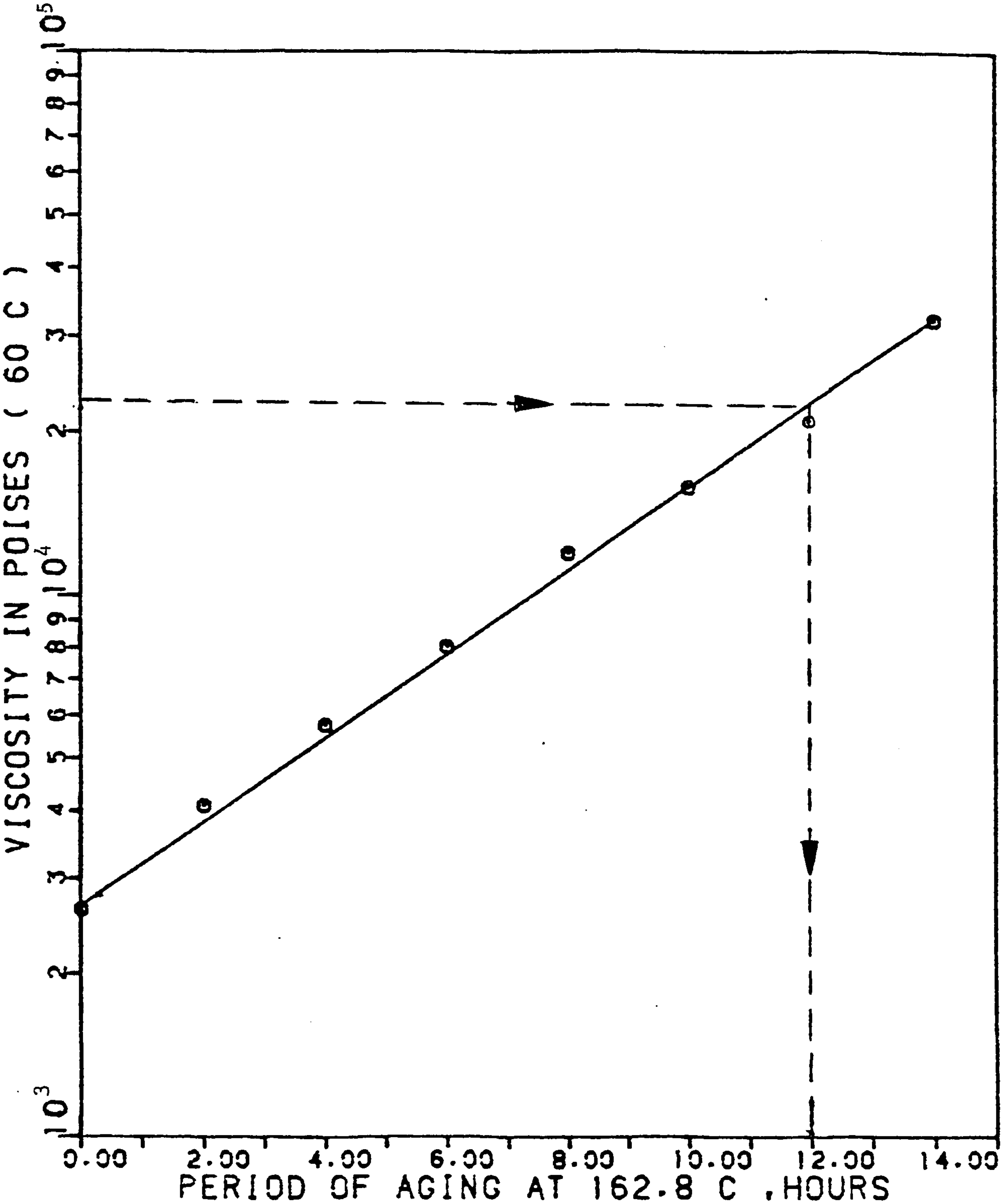


Fig. 3.7 : Hardening of Virgin Asphalt with Period of Heating in Thin Film Oven Test

Table 3.11: Flash Point Temperature of Asphalt Blended with Diesel Oil

% Diesel by Weight of Total Blend*	Flash Point Temperature ASTM D92-78 °C	(°F)
3%	226.7	(440)
4%	196.1	(385)
5%	171.1	(340)

* With Virgin Asphalt

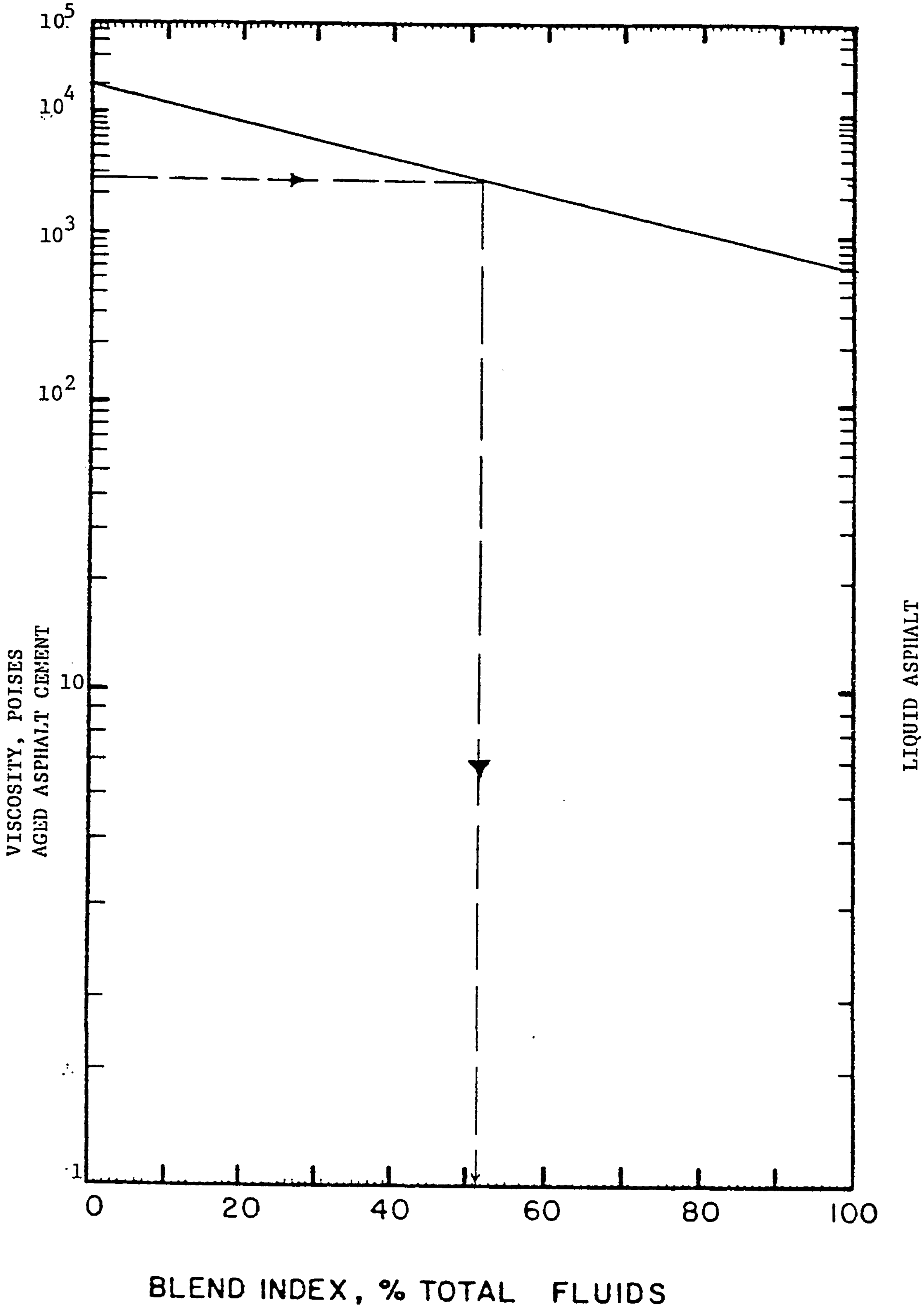


Fig. 3.8: Graphical Procedure to Determine Percentage of Liquid Asphalt in Blend with Aged Asphalt.

Table 3.12: Physical Properties of Sulphur-Asphalt Binders [35]

	Composition, % by wt.					
85-100 Pen. Asphalt	100	90	80	70	60	50
Elemental Sulphur	0	10	20	30	40	50
Specific Gravity, at 60°F	1.027	1.055	1.120	1.183	1.235	1.344
Softening Point, F ASTM D36	116	104	106	105	110	112
Penetration, 77°F 100 g, 5 sec	87	157	175	170	174	65
Fraas Breaking Point, °C IP80	-16	-12	-14	-14	-13.5	--

85-100 pen grade of asphalt blended with different percentages of sulphur. The SA binder possesses lower softening point and greater penetration upto 40 percent sulphur substitution. The viscosities of SA binders at 60°C (140°F) and 138°C (280°F) are given in Table 3.13 (36) which shows lower viscosities for sulphur substitution upto 40 percent by weight. Further, sulphur becomes solid at temperatures below 119°C (246°F), and therefore has the potential for long life durability as it will not volatalize from the pavement during service. Bulghunaim and Tons (37) studied the long term maturity of sulphur-asphalt and typical results of maturity over a period of 1 year are presented in Fig. 3.9 for different percentages of sulphur. For 30 percent sulphur, although initial penetration values were high, the final penetration after 364 days of maturity was very similar to that of virgin asphalt. In hot mix recycling operation, Wisconsin DOT adds a 70 percent virgin asphalt - 30 percent sulphur mixture to the process (4). Since elemental sulphur is produced in the Kingdom as a compulsory by-product from large gas gathering plants, it is readily available. Previous research in utilization of sulphur in road paving showed two major problems, viz. cracking under heavy traffic loads, which would be attributed to high sulphur/asphalt ratio of 45:55, and stripping of sulphur asphalt with certain types of aggregates (38). In this research, the sulphur-asphalt ratio was, therefore, limited to 30:70 and use of modified sulphur of commercial grade, Chement 2000, was also investigated along with the elemental grade. The physical properties of sulphur asphalt blend using the two types of sulphur are given in Table 3.14.

Table 3.13: Viscosities of Sulphur Asphalt Binders [36]

Sample Description	Sulphur Content % Wt.	Viscosities ASTM D2171 140°F, Poise	Brookfield 280°F, C.S.
85/100 Pen. A.C.	Nil	1557	318
S/A binder	10	570	205
S/A binder	20	691	145
S/A binder	30	772	153
S/A binder	40	950	148
S/A binder	45	1077	168
S/A binder	50	2494	380
S/A binder	60	5081	583

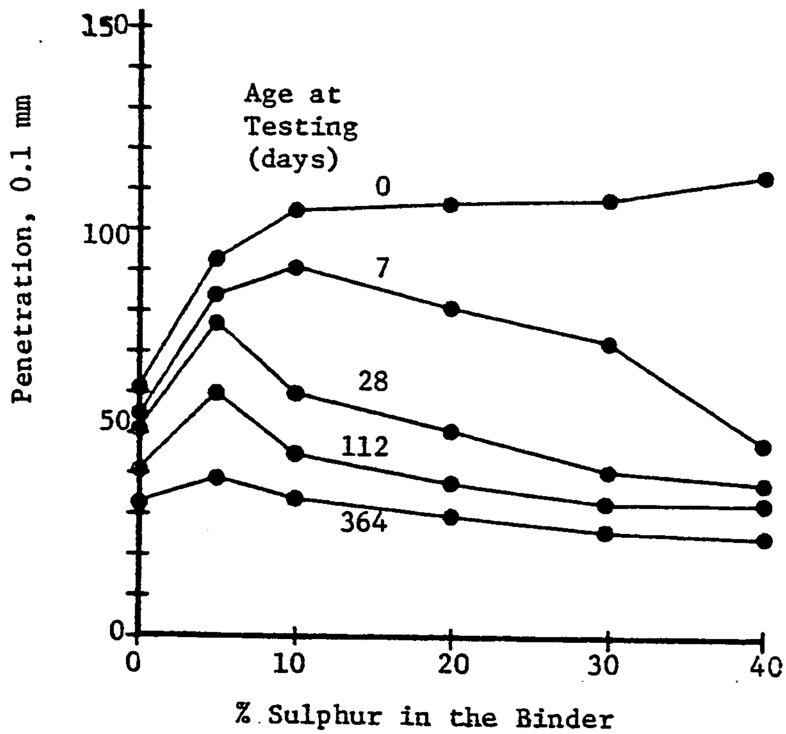


Fig. 3.9 : Effect of Age on Hardening of Sulphur-Asphalt Binder (37).

Table 3.14: Properties of Sulphur-Asphalt Blend

(A) Elemental Sulphur + Asphalt (30/70 weight ratio)

Penetration at 25°C, ASTM D5-73 = 119.3

Viscosity at 60°C, ASTM 2171 = 938.6 poises

(B) Modified Sulphur + Asphalt (30/70 weight ratio)

Penetration at 25°C, ASTM D5-73 = 102.0

Viscosity at 60°C, ASTM 2171 = 1415.2 poises

3.6.3 Hardening Characteristics of Various Blends

Blends of mobilsol, dutrex and liquid asphalt with artificially aged asphalt were prepared employing the blending percentages determined as explained in Section 3.6.2. The blends were then subjected to artificial hardening in oven at 162.8°C (325°F) with air circulated for a varying period upto 12 hours. The viscosity values of the blends were determined after varying period of weathering and the results are plotted in Fig. 3.10. The aging characteristics of virgin asphalt were also tested simultaneously and results are plotted in the above figure. The poor performance of liquid asphalt in comparison to virgin asphalt is clearly noted. Therefore, liquid asphalt, i.e. blending of diesel with virgin asphalt, cannot be recommended for use in recycling as diesel may volatilize much faster leaving the asphalt brittle. Further testing for recycling potential was, therefore, made only with the remaining four types of modifiers, viz. mobilsol, dutrex, elemental sulphur and modified sulphur.

3.7 Mixture Design Using Marshall Testing

Asphalt content plays a very important role in the properties of mixtures. Therefore, it must be pointed out that the blend should always be mixed with aggregate to check whether it gives the optimum mixture property or not. This means that determining the amount of a modifier with the blending curve is not sufficient and the mixture property should always be examined by means of a suitable mix design procedure. When the blend is found not to give the optimum mixture

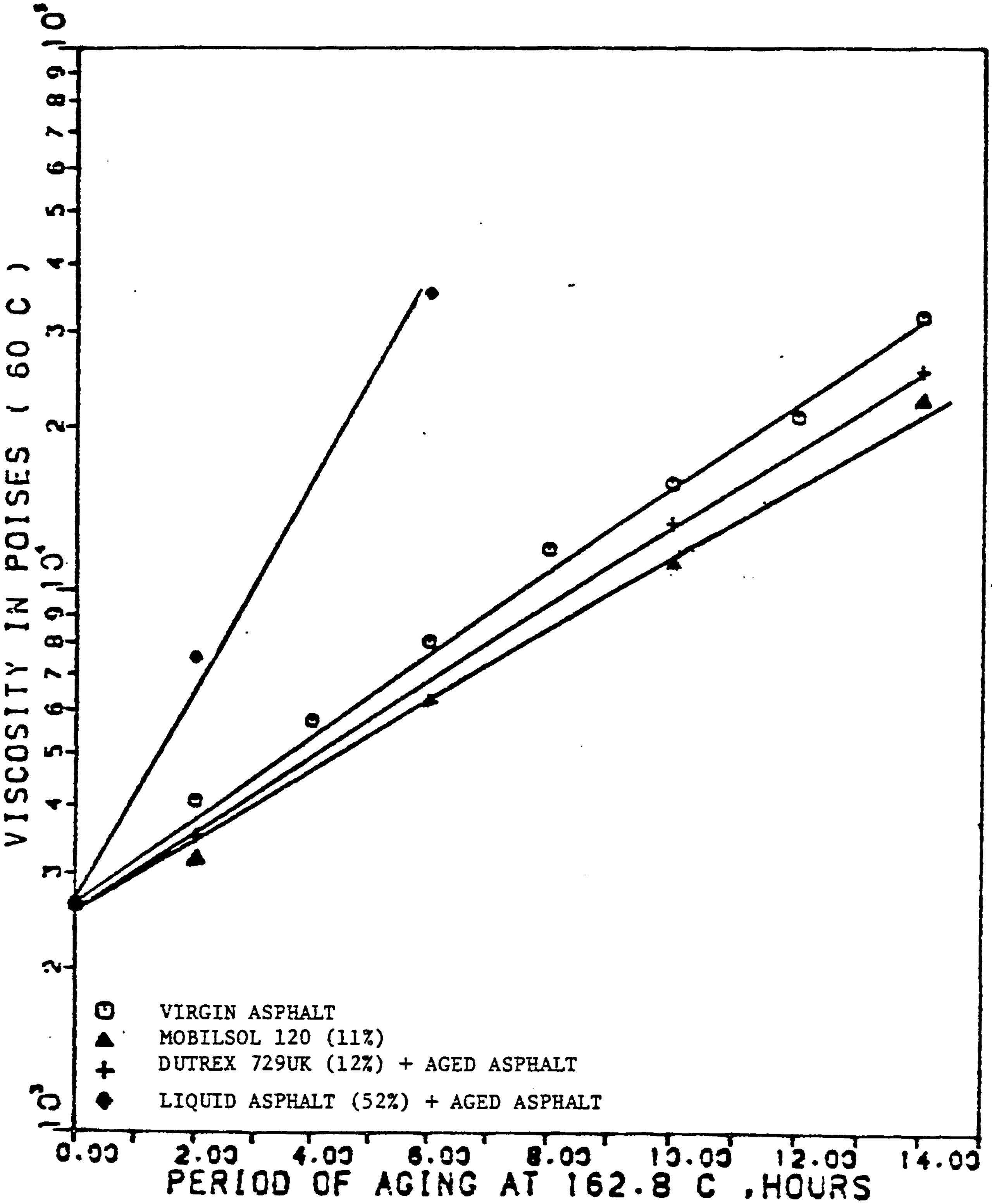


Fig. 3.10 : Effect of Artificial Hardening on Blend Viscosity

property, some remedies to adjust the excessive asphalt, such as addition of virgin aggregate, should be taken.

3.7.1 Mixture Constituents and Types

In all five test series were conducted employing Marshall method of mix design. Four test series used modifiers selected as discussed in section 3.6, viz. mobilsol, dutrex, elemental sulphur and modified sulphur. The corresponding recycled asphalt mixtures henceforth are designated as MBA (mobilsol-asphalt), DTA (dutrex-asphalt), ESA (elemental sulphur-asphalt) and MSA (modified sulphur-asphalt) mixes, respectively. Each of the above mixtures comprised crushed asphalt pavement, modifier of suitable quantity (section 3.6.2), virgin aggregate to correct aggregate grading deficiencies in reclaimed pavement and virgin asphalt to meet asphalt demand of additional aggregate including the reclaimed pavement. The fifth test series comprised specimens fabricated from the virgin hot asphaltic concrete mixture without addition of any modifier or reclaimed pavement. This test series, designated as VRA (virgin asphalt concrete), was used as a basis of comparison with other test series employing the recycling mixtures.

3.7.2 Estimation of Optimum Binder Demand

Marshall method ASTM D1559 was used for mix design. Optimum binder content with pure asphalt was initially estimated from the following approximate formula of Asphalt Institute (1) based on aggregate gradation.

$$P_c = 0.035a + 0.045b + 0.18c + F \qquad \text{Eq. 3.2}$$

where,

P_c = percent of asphalt material by weight of total mix,

a = percent of mineral aggregate retained on No. 8 seive,

b = percent of mineral aggregate passing No. 8 seive and retained on No. 200 seive,

c = percent of mineral aggregate passing No. 200 seive,

F = 0 to 2.0 percent based on absorption of light or heavy aggregate. In the absence of other data a value of 0.7 to 1.0 should cover most conditions.

The optimum asphalt content as determined from the above equation was 5.5 percent. For ESA and MSA series this represented lower limit for asphalt content. Since sulphur is about twice as dense as asphalt, it requires twice the weight of sulphur to replace an equal volume of asphalt. The upper bound of sulphur-asphalt (SA) binder level which is equal to the weight of an equal volume of asphalt was obtained by the approximate formula of US Bureau of Mines (27) as follows.

$$\text{SA (equivalent volume) wt-pct} = 200A/200\text{-}P_s \qquad \text{Eq. 3.3}$$

where A is weight percent asphalt in conventional design, and P_s is weight percent sulphur in SA binder.

The optimum binder demand as actually determined from the design of VRA mix was obtained as 5.3 percent. The volume equivalent

SA binder level corresponding to 5.3 percent optimum asphalt binder was obtained from Eq. 3.3 as 6.2 percent by weight of total mix for selected sulphur/asphalt weight ratio of 30/70.

3.7.3 Percent of New Asphalt in Recycled Mixture

The quantity of new asphalt to be added to the recycled mixture equals the calculated asphalt demand minus the quantity of asphalt in the reclaimed asphalt pavement and also minus the quantity of recycling agent used. This was found to be 2 percent for MBA and DTA and 2.7 percent for ESA and MSA. Typical calculations are given in the Appendix.

3.7.4 Trial Mix Design Alternatives

Keeping percent modifier constant in the mix for MBA and DTA at 11 percent and 12 percent respectively, and varying the new asphalt in 0.5 percent increments above and below the estimated amount. Marshall briquettes were fabricated following the ASTM D1559. For MSA and ESA mixtures, the same procedure was followed except that in these series the amount of sulphur used was also varied with quantity of new asphalt, keeping the sulphur-asphalt ratio constant at 30/70 (by weight).

3.7.5 Preparation of Laboratory Specimens

Prior to mixing, crushed pavement, virgin aggregate and virgin asphalt were heated separately for a period of 2 hours at 146°C

(295°F). The crushed pavement was heated in a covered pan. For mobilsol and dutrex, during the last 15 minutes of the period, the specified amount of modifier was placed in a closed container and heated to approximately 94°C (220°F). At the end of two hours, the constituents were transferred to the mixer. The modifier was added to the crushed pavement and mixing started. Virgin aggregate and virgin asphalt in hot state were immediately introduced to the mixer in the above order. The mixing was carried out in Hobart automatic mixer and continued for a total period of 2 minutes. This was found to be adequate to give a homogeneous, well coated mix, without any appreciable drop (less than 6°C) in temperature. In case of sulphur, no undue fumes of hydrogen sulphide and sulphur dioxide were noticed. The mixture was covered and placed back in the oven at 130°C (266°F) for 30 minutes prior to compaction. Compaction was carried out with Marshall hammer giving 75 blows on each side.

3.7.6 Marshall Test

In order to determine the optimum binder content for each test series, Marshall testing was conducted at 60°C (140°F) following the procedure in ASTM D1559. The percentages of air voids in the specimens were determined from the bulk specific gravity of the specimens (ASTM D2726) and the maximum theoretical specific gravity of the voidless mix (ASTM D2041). Stability loss, after 24 hour immersion in water at 60°C (140°F), was also determined to check the resistance to stripping which was estimated on the basis of Marshall strength index calculated by dividing the stability of the specimens conditioned in water for 24 hr by normal $\frac{1}{2}$ hr stability.

The test results are presented in Figs. 3.11 to 3.15. Each point is an average of triplicate test specimens. Asphalt contents were determined corresponding to the following :

(a) Maximum stability

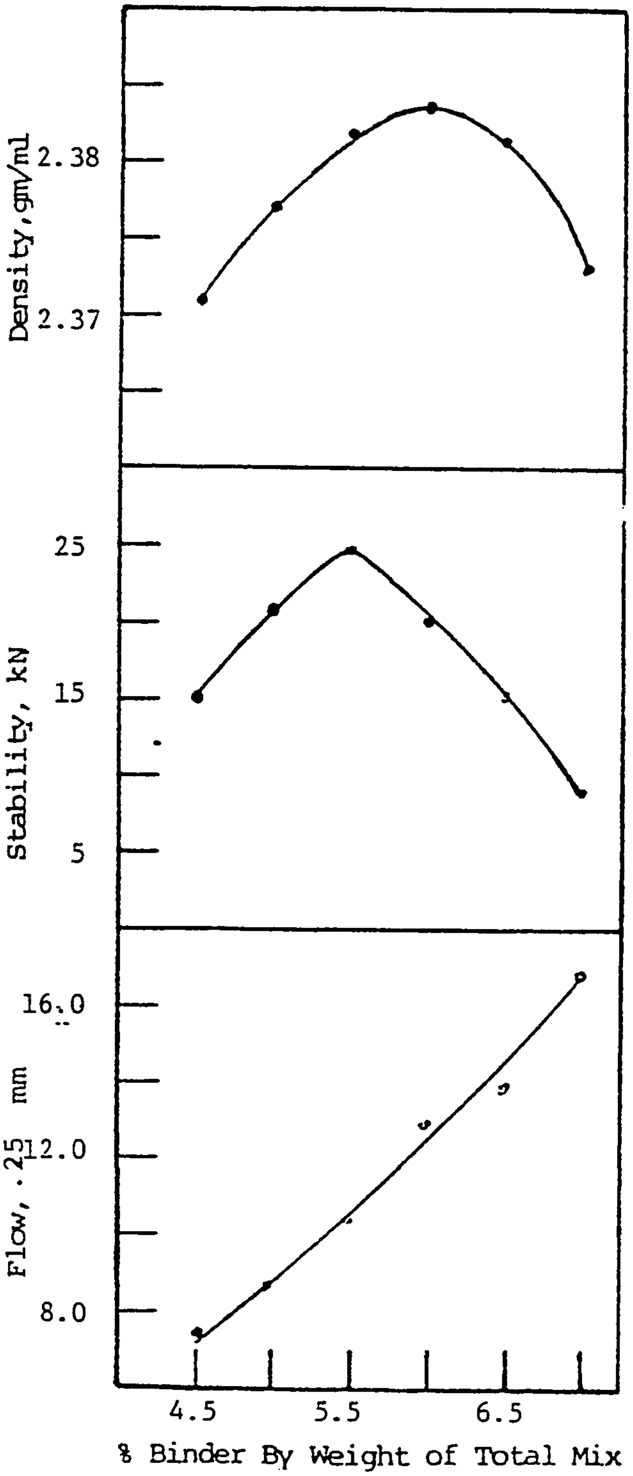
(b) Maximum unit weight

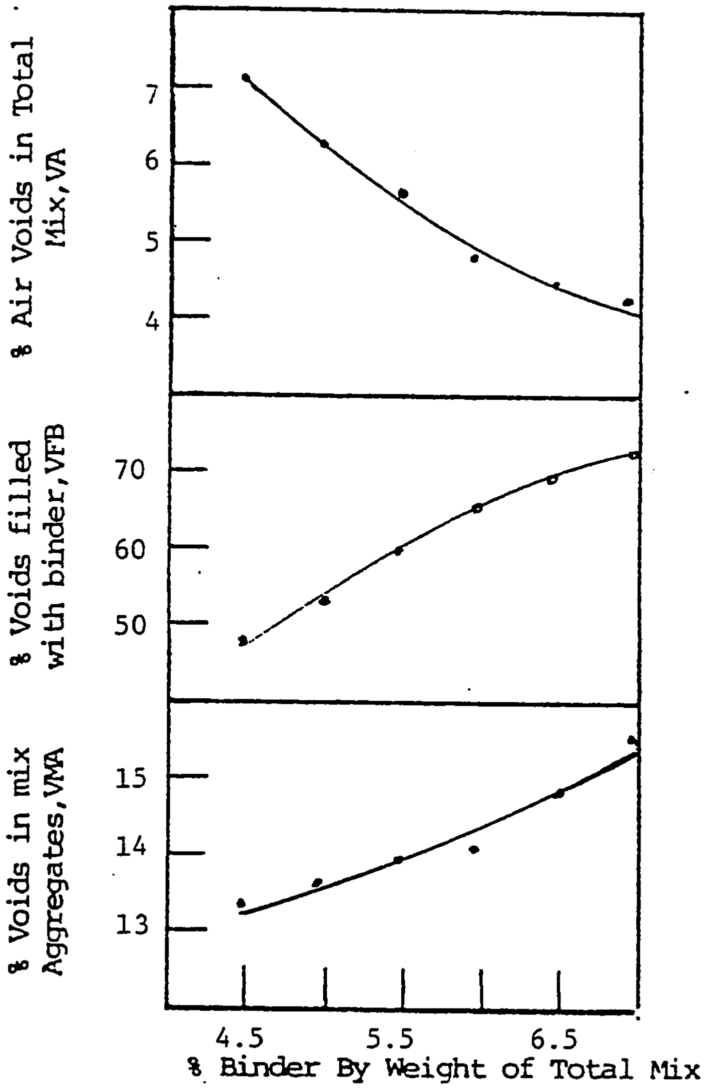
(c) 4 percent air voids.

The optimum asphalt content of the mix was then calculated as the numerical average of the values of the asphalt contents determined as noted above.

3.7.7 Marshall Properties

The Marshall properties were then determined at the optimum binder percentage for each test series using the curves shown in Figs. 3.11 to 3.15. They are summarized in Table 3.15 and in Figs. 3.16 to 3.18. Marshall design criteria for heavy traffic is given in Table 3.16. Each recycling mixure, like the virgin asphalt concrete (VRA) mix, is found to satisfy the Marshall design criteria. Higher flow values and higher stability values are encountered with all recycled mixtures in comparison to the virgin asphalt concrete indicating excellent adaptability of failed asphalt pavement to recycling process. Similarly higher immersion strength index is obtained in comparison to VRA mix indicating superior resistance of recycled mixture to water induced damage. Similar results were obtained by Epps et al (39) on central plant recy-



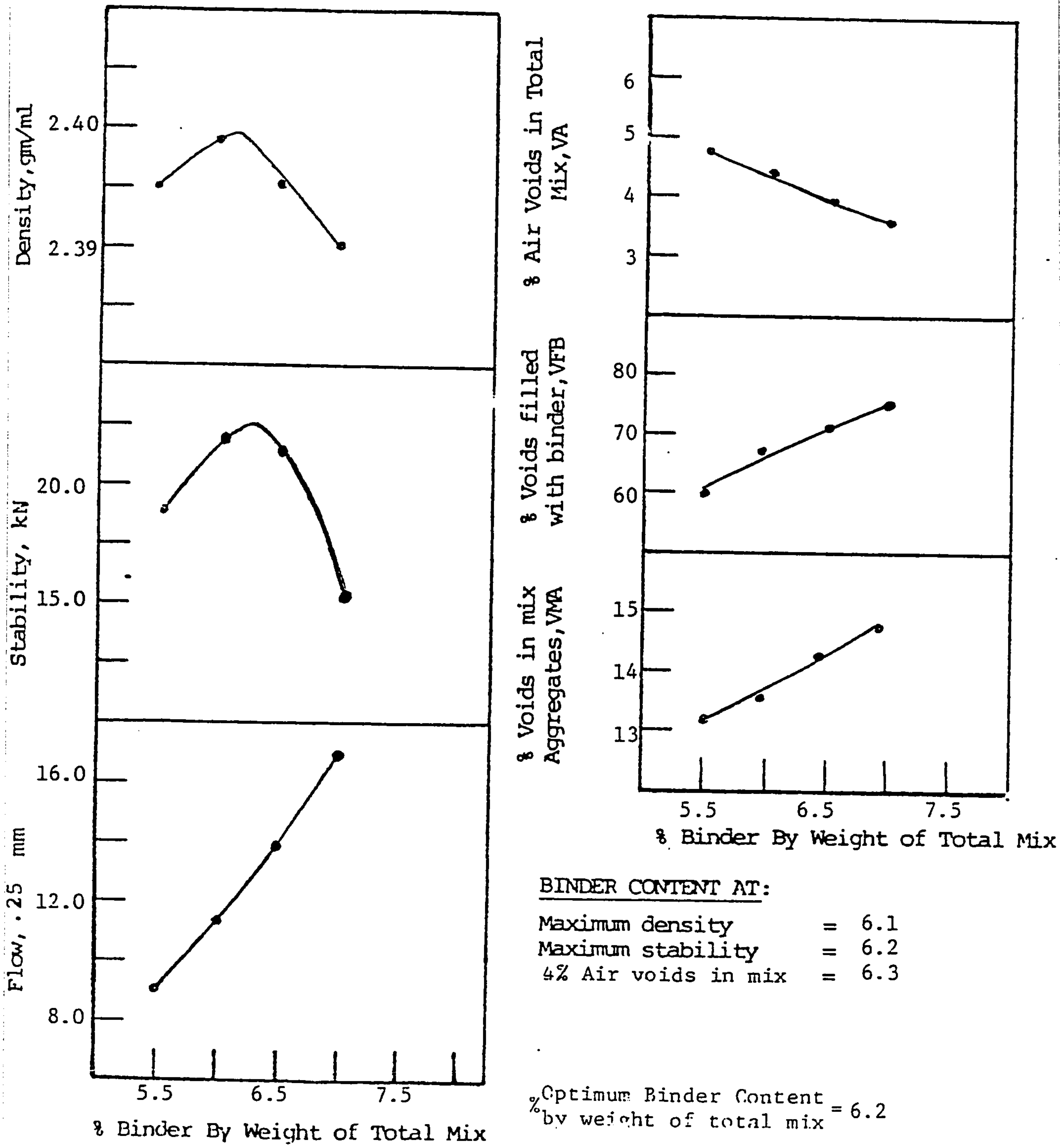


BINDER CONTENT AT:

Maximum density	=	6.1
Maximum stability	=	5.5
4% Air voids in mix	=	7.0

% Optimum Binder Content by weight of total mix = 6.2

Fig. 3.11 : Marshall Mix Design Curves for MSA Mix

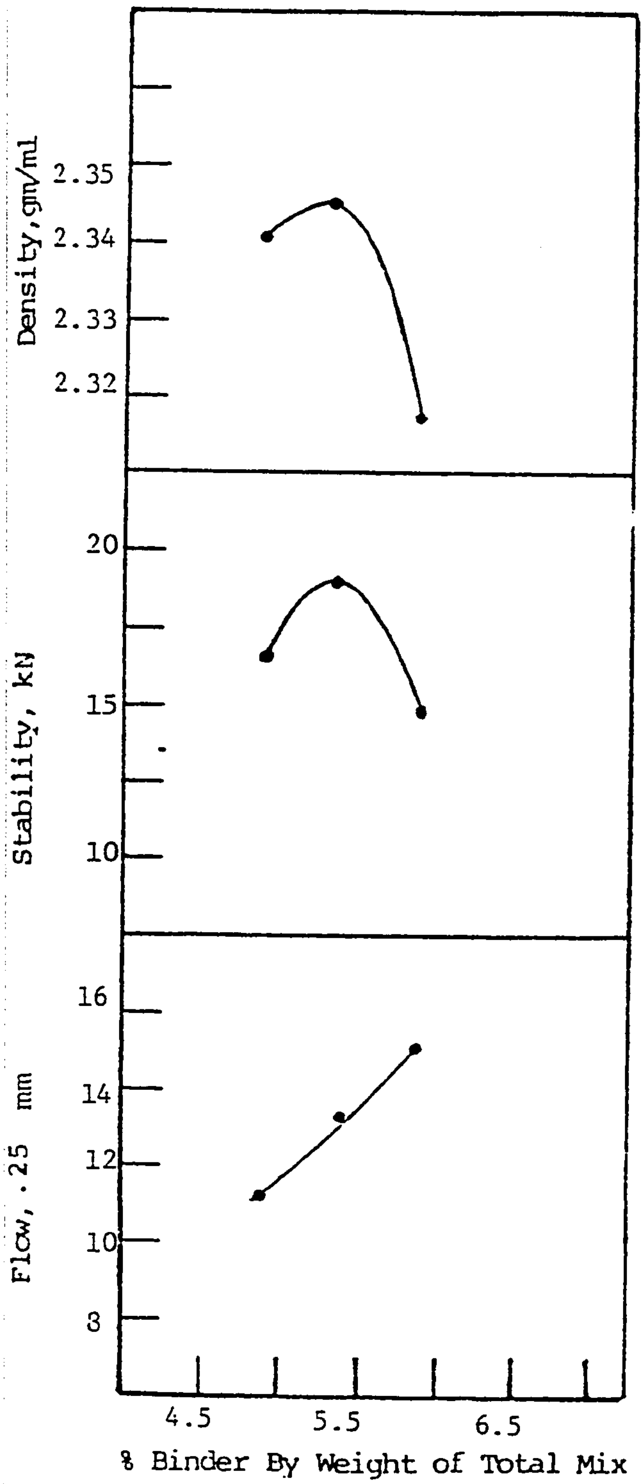


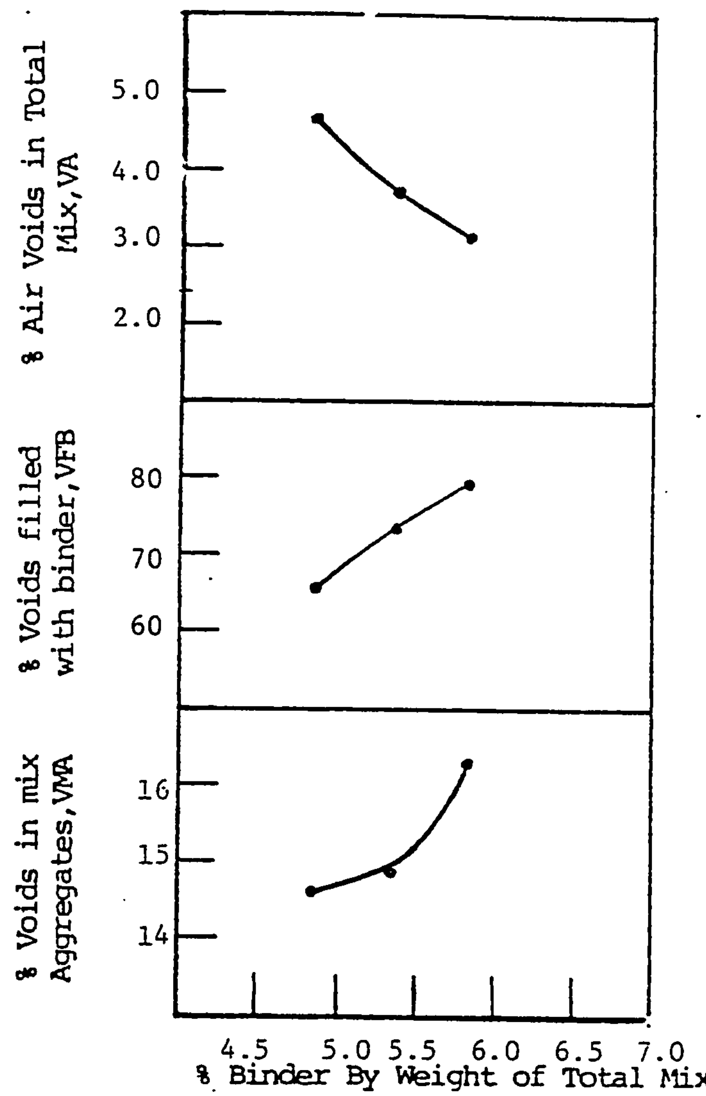
BINDER CONTENT AT:

Maximum density	=	6.1
Maximum stability	=	6.2
4% Air voids in mix	=	6.3

% Optimum Binder Content by weight of total mix = 6.2

Fig. 3.12 : Marshall Mix Design Curves for ESA Mix





BINDER CONTENT AT:

Maximum density = 5.3
Maximum stability = 5.25
4% Air voids in mix = 5.25

% Optimum Binder Content by weight of total mix = 5.3

Fig. 3.13 : Marshall Mix Design Curves for MBA Mix

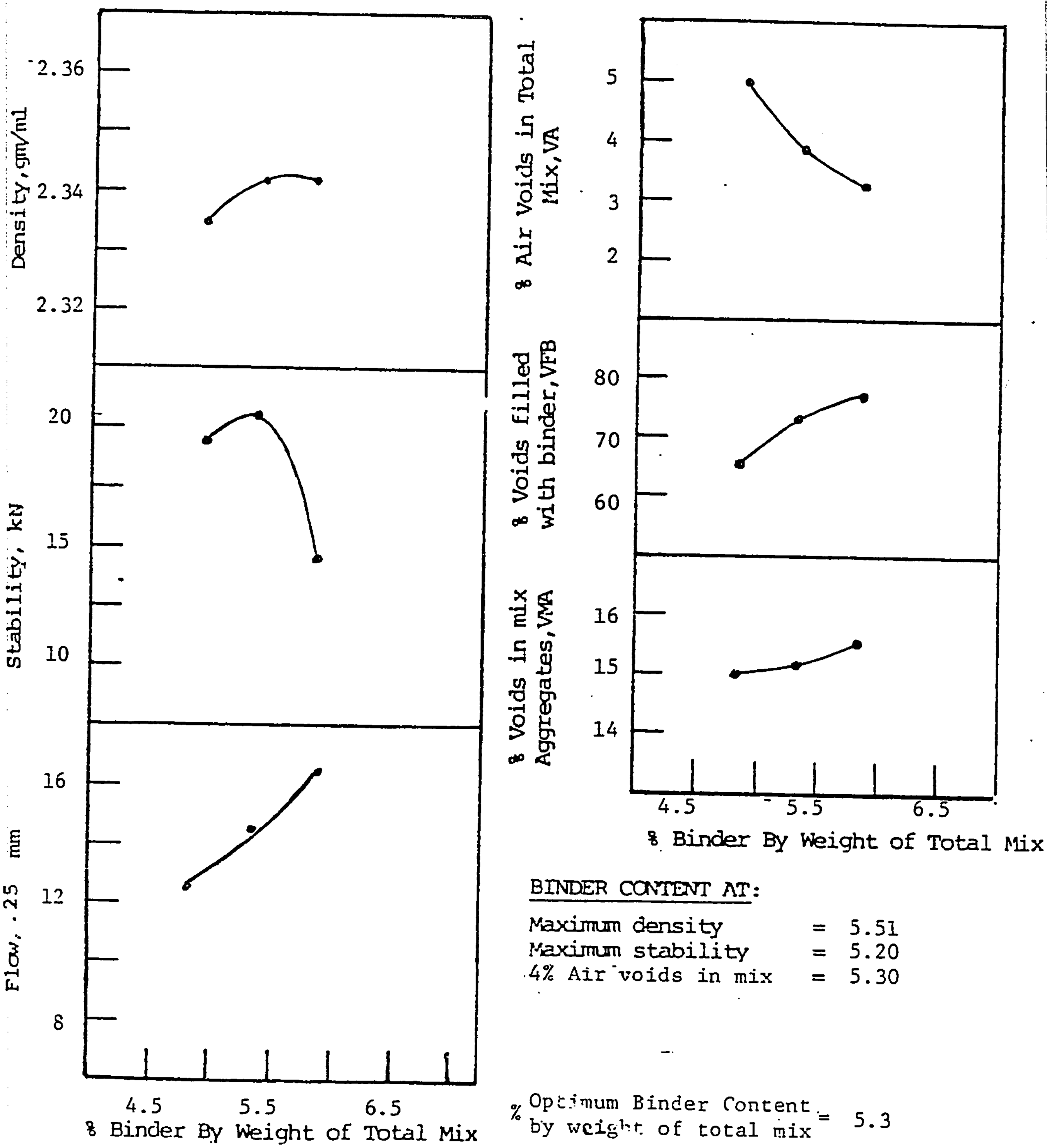


Fig. 3.14 : Marshall Mix Design Curves for DTA Mix.

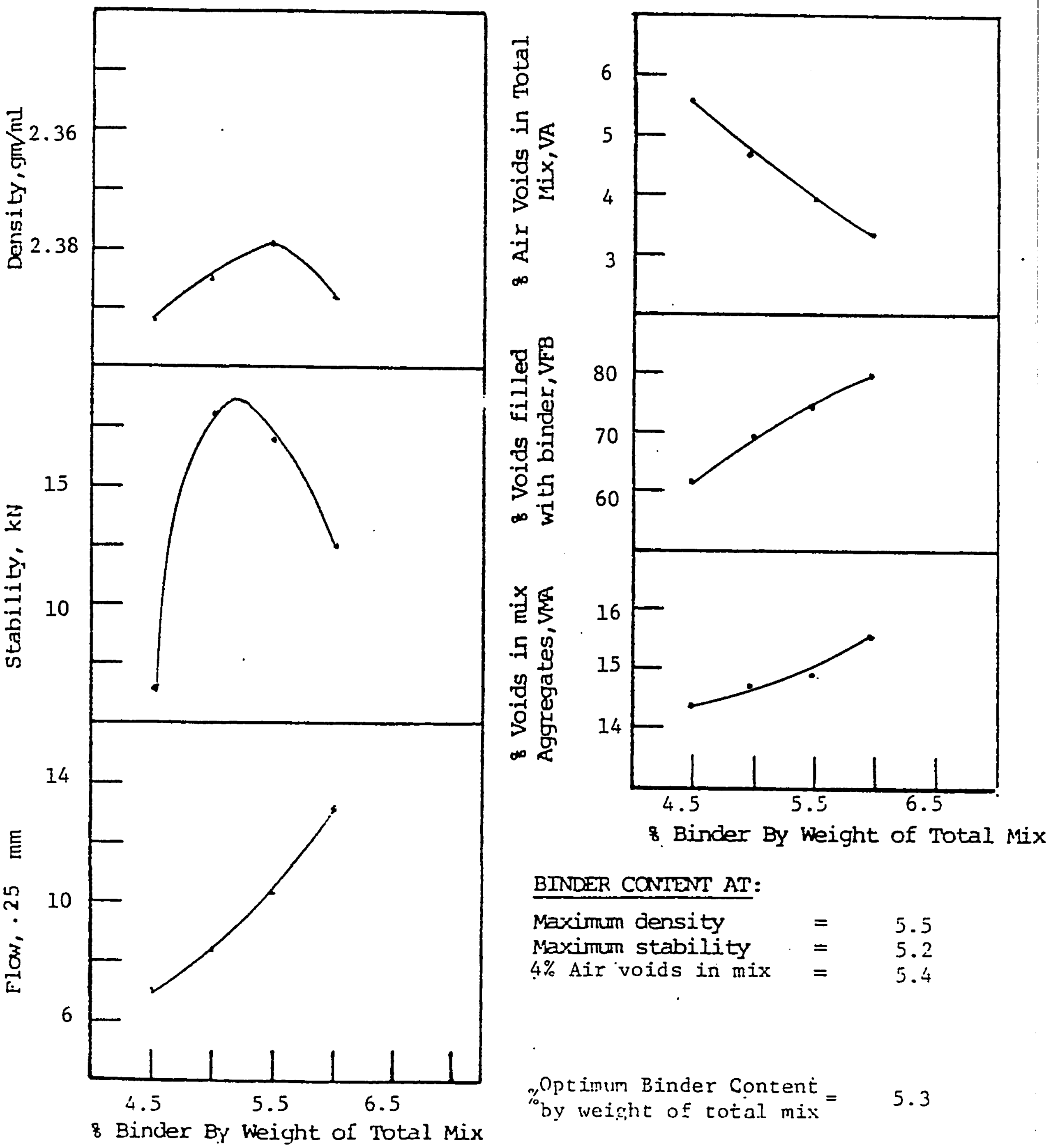


Fig. 3.15 : Marshall Mix Design Curves for VRA Mix

Table 3.15: Marshall Properties of Various Test Series

Mix Type	Optimum Binder	½ hr Stability kN (lb)	Flow 0.25 mm	Air Voids %	VMA %	24 hrs Stability kN (lb)	Strength Index %
MSA	6.2	18.5 (4159.2)	13.3	4.4	14.5	22.3 (5048.1)	121.3
ESA	6.2	22.45 (5047.2)	12.6	4.1	14.0	22.2 (4989.7)	98.9
MBA	5.3	19.0 (4272.4)	13.5	3.9	15.0	16.6 (3732.6)	87.5
DTA	5.3	20.5 (4608.8)	14.3	4.0	15.1	17.7 (3982.5)	86.4
VRA	5.3	18.25 (4103.0)	9.6	4.1	14.8	13.9 (3118.3)	76.0

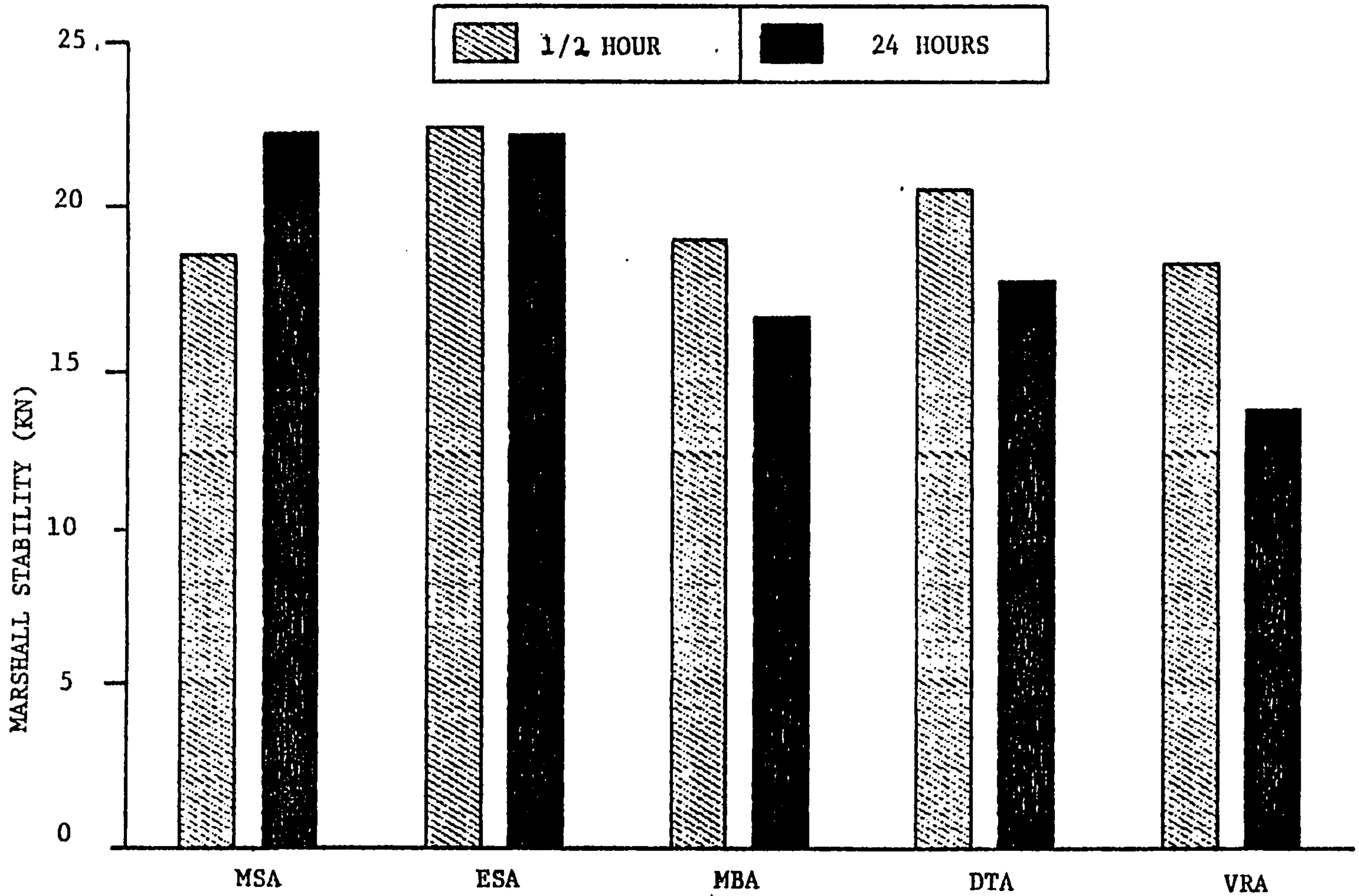


Fig. 3.16 : Marshall Stability Values at Optimum Binder Content

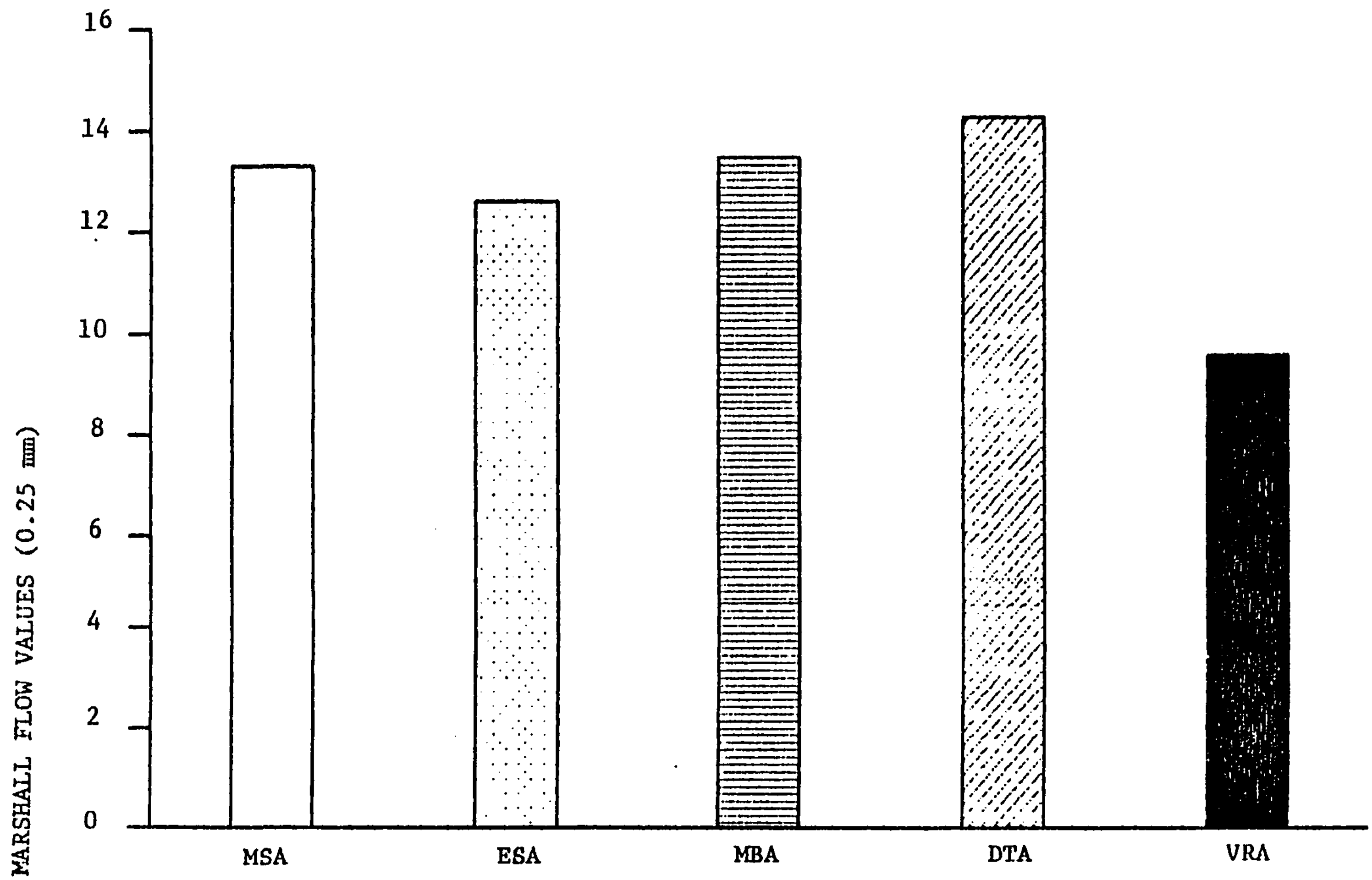


Fig. 3.17: Marshall Flow Values at Optimum Binder Content

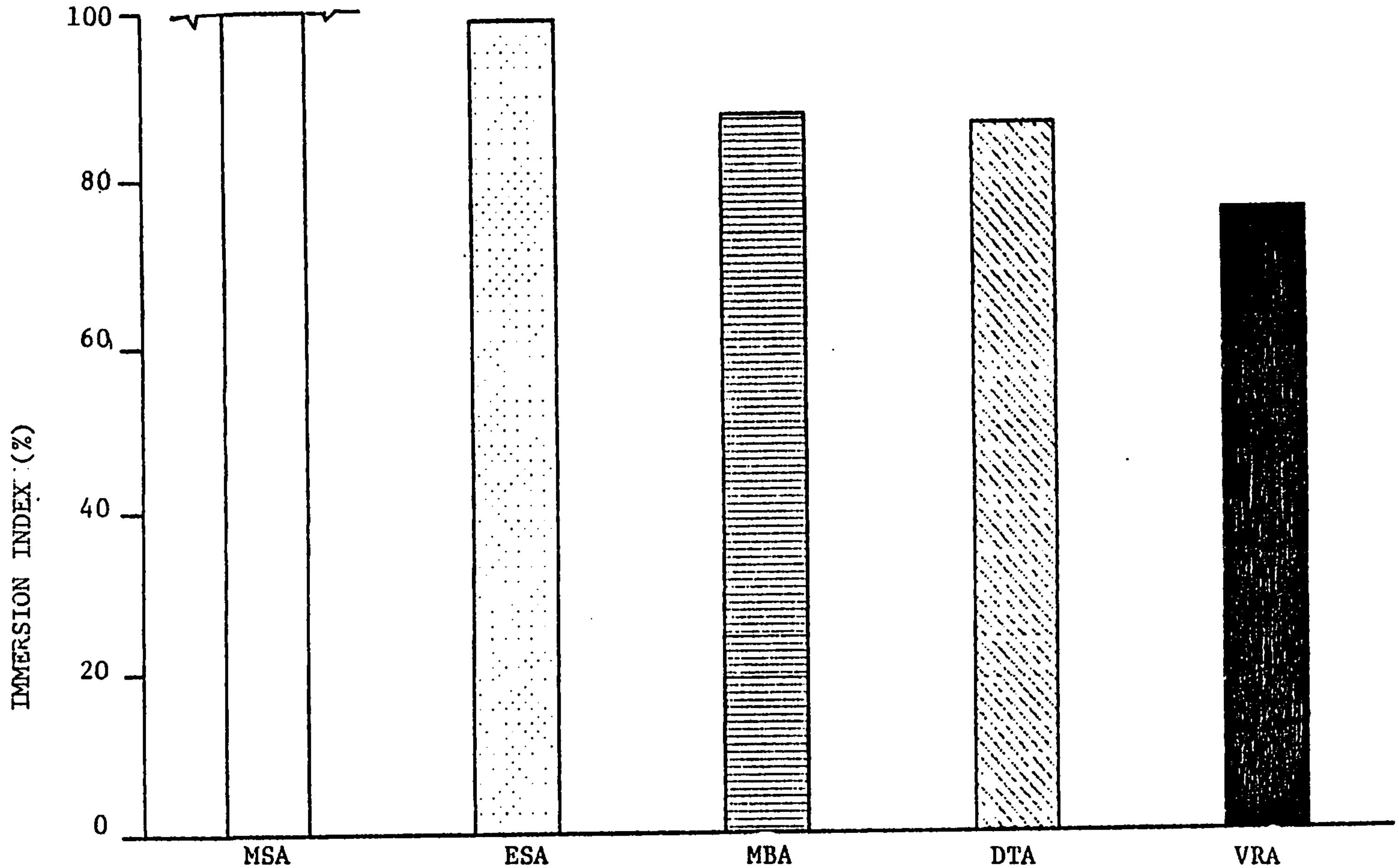


Fig. 3.18 : Marshall Immersion Index Value at Optimum Binder Content

Table 3.16: Marshall Mix Design Criteria (29)

Marshall Method Mix Criteria	Light Traffic Surface & Base		Medium Traffic Surface & Base		Heavy Traffic Surface & Base	
	Min.	Max.	Min.	Max.	Min.	Max.
Compaction, number of blows each end of specimen	35		50		75	
Stability,N (lb.)	2224 (500)	-	3336 (750)	-	6672 (1500)	-
Flow, 0.25 mm (0.01 in.)	8	20	8	18	8	16
Percent Air Voids	3	5	3	5	3	5
Percent Voids in Mineral Aggregate (VMA)	varies with aggregate gradation					

cled material. With respect to MSA, Figure 3.18 shows gain in strength with prolonged curing at 60°C which may be attributed to some kind 'gel' formation due to presence of a cementing agent in the modified sulphur used. Similar behavior was noticed with virgin sulphur (elemental)-extended-asphalt hot-mix employing Portland cement as an additive to improve the water induced damage (38).

Chapter 4

DYNAMIC TESTING

4.1 Introduction

The Marshall properties determined in the previous chapter are unable to predict the stress-strain behavior of the pavement layer under the actual traffic and temperature conditions. Knowledge of stress-strain response of a paving mixture is important to predict its resistance to fatigue cracking and plastic deformation, the latter showing on the pavement surface in the form of rutting. Dynamic testing in this study constituted the resilient modulus tests, the fatigue life tests and the permanent vertical deformation tests. Static tensile strength tests were also performed. All the tests were conducted on Marshall briquettes which were fabricated at the optimum binder content determined as described in Chapter 3.

The briquettes were tested in indirect split tensile testing mode, both for static as well as dynamic testing. These tests and their results are discussed in detail in the following sections.

4.2 Repeated Loading Equipment (40)

The repeated loading equipment used for dynamic testing is shown in Fig. 4.1. It includes an airpowered testing apparatus and a control cabinet from which dynamic and static load can be controlled. Electro-pneumatic system is used to apply loads. It consists of a Bellofram air

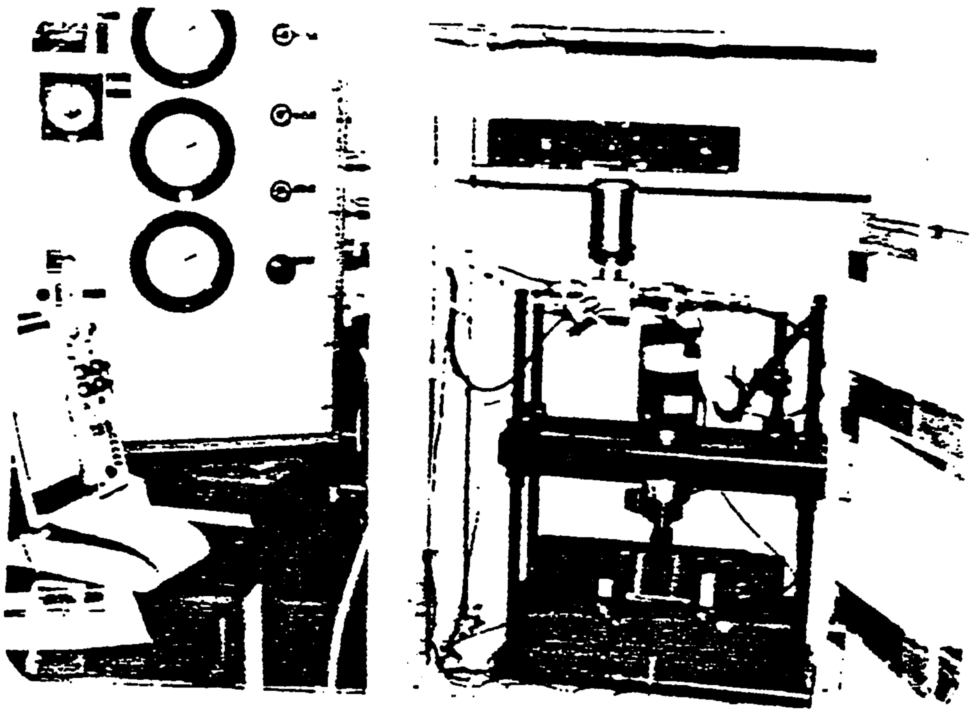


Fig. 4.1 : Repeated Loading Equipment Used (41)

cylinder, a shuttle valve and a Mac valve. The shuttle valve regulates airflow to the bellofram air cylinder and is designed to allow the line of highest pressure lines, and electrical signals to the Mac valve are monitored from the control cabinet.

Precision air regulators and pressure gages provide good control of the static, dynamic and confining air pressure lines. Two timers control the electrical signal to the Mac valve (pulse interval and pulse duration), and a counter to record the number of pulse loads.

An important feature which controls the operation mode of the Repeated Load Test System is the fatigue-modulus switch. The off position disconnects the timers. This setting is particularly useful during testing, such as when moving a specimen in or out of the testing apparatus. The modulus position is the normal testing mode. In this position the timers and, therefore, both the counter and the dynamic load are activated. The fatigue position is used only when running fatigue tests.

The loading apparatus is housed in an environmental chamber so that the tests can be conducted at designated temperature ranging from -20 to 85°C. Specimens were kept inside the chamber about 4 hours prior to testing to enable the specimens to reach the specified temperature required for testing.

All tests were run on 10 mm (4 in.) diameter Marshall specimens fabricated at the optimum binder content. Testing conditions which were kept constant in each case are summarized as follows :

(1) A static load of 44.5 N (10 lbs) was applied to hold the sample

in place.

(2) The dynamic load duration was fixed at 0.1 seconds and the load frequency at 60 cycles per minute.

(3) Repetitive load was applied corresponding to initial horizontal tensile strain of 100 microstrains.

(4) Test temperature was defined as the average sample temperature during testing (variable for resilient modulus test and at 40°C (104°F) for fatigue test).

(5) Load platens were 13 mm (1/2 in.) wide.

4.3 Resilient Modulus

This test provides an important input for the structural design of pavement system using multi-layer elastic theory for design. The test set-up is shown in Fig. 4.2 which is taken from Reference (41). A diametral yoke was used to measure the horizontal deformation of cylindrical specimen subjected to dynamic vertical loading. The horizontal deformation of cylindrical specimen subjected to dynamic vertical loading was measured by two transducers while the load applied was measured by using a flat load cell. Typical traces of load and deformation as recorded by a two-channel Hewlett-Packard Model 7402A Oscillographic recorder are shown in Fig. 4.3 (41).

Resilient modulus value was computed using the following equation (42) converted into equivalent SI units.

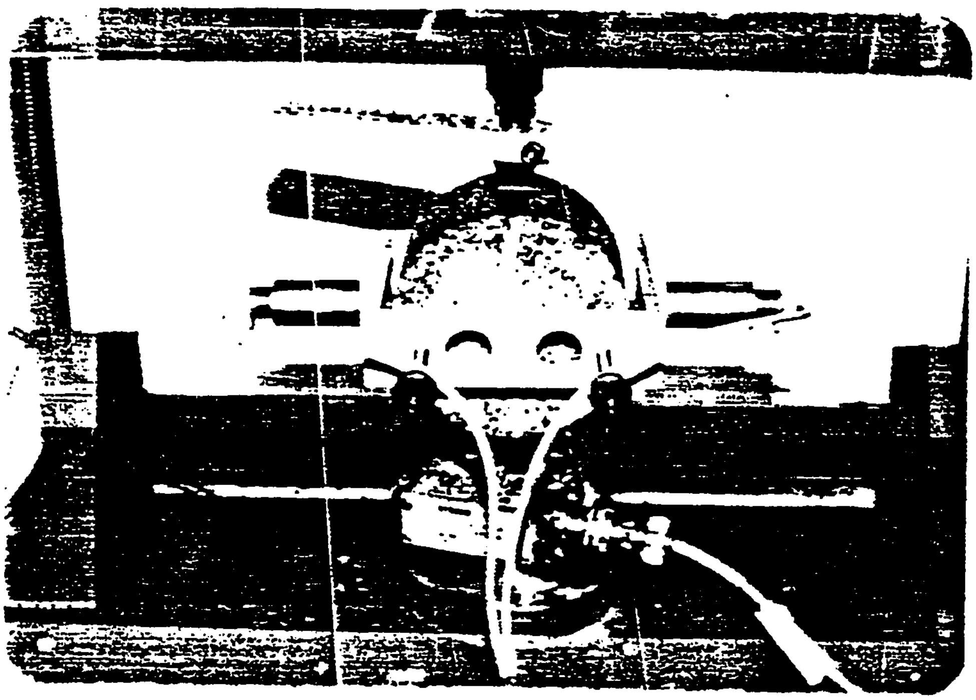


Fig. 4.2 : Resilient Modulus Test Setup (41)

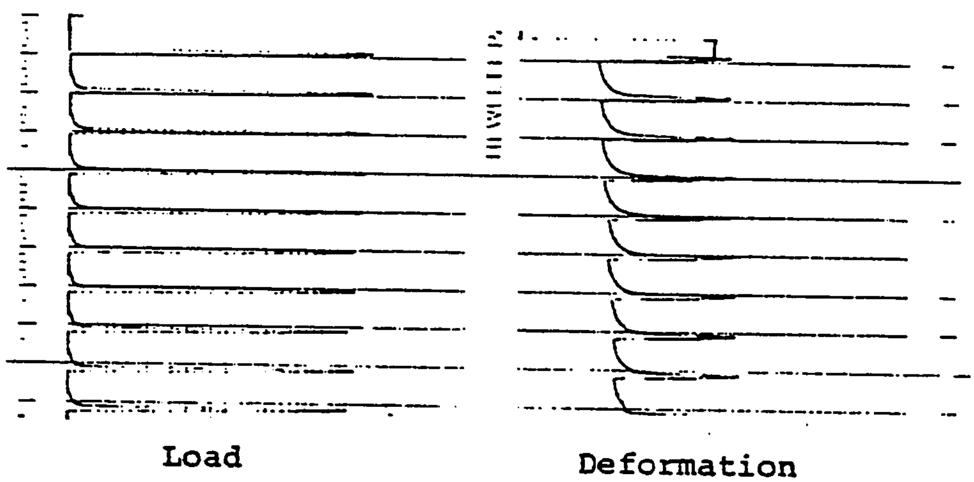


Fig. 4.3 : Typical Load and Deformation Traces (41)

$$\text{Resilient Modulus (MPa)} = 10^3 P\,(0.9974\mu + 0.2692)/h.\Delta \qquad \text{Eq. 4.1}$$

where

P = applied load, kN

h = thickness of specimen, mm

Δ = recoverable horizontal deformation across the sample, mm

μ = Poisson's ratio (assumed as 0.35)

The dynamic load was adjusted to give the desired initial tensile strain of 100 microns. Following equation converted into S.I. unit, was used to compute tensile strain from the measured recoverable horizontal deformation

$$\Sigma_t = \Delta \times 0.02048 \qquad \text{Eq. 4.2}$$

where

Σ_t = horizontal elastic tensile strain

Δ = horizontal elastic tensile deformation, mm

Resilient modulus of the mix is considered to provide a good index of binder stiffness. In order to study the effect of binder aging on resilient modulus value, the latter was determined after curing the specimens as follows :

(i) One day room curing at 22.2 - 23.3°C (72-74°F)

(ii) 7 day room curing at the above temperature.

(iii) 7 day heat soaking at 60°C (140°F) to simulate long term effect of heat and oxidation of asphalt under inservice conditions.

The results are summarized in Table 4.1 and Fig. 4.4. Higher moduli values are encountered with sulphur-asphalt recycled mixtures for both MSA and ESA test series. For one day room curing,the resilient modulus values of MBA, DTA, ESA and MSA mixes are 0.82, 0.74, 1.67 and 1.50 times that of the virgin control mix (VRA). There is no significant effect of room curing period on moduli values of the recycled mixtures using hydrocarbon based modifiers viz. the MBA and DTA mixes, which also is the case for the control mix VRA. However, sulphur based mixtures viz. MSA and ESA show significant increase in the resilient modulus in seven day room curing which is found to be 52.86 and 39.37 percent, respectively, above the 1 day room cure values. Effect of 7 day heat soaking is again more prominent with MSA and ESA series, increasing the moduli value above the 1 day cure by 121.57 and 91.17 percent, respectively. This may be attributed to the combined effect of hardening of asphalt binder and the recrystallization of sulphur known to occur with age. Effect of hardening of asphalt in the control mixture is also obvious since its modulus value increased by 60.15 percent due to 7 day heat soaking. However, the recycled mixtures MBA and DTA have not exhibited any significant increase in M_R due to accelerated heat conditioning, the increment being 7.03 and 8.34 percent, respectively. Moduli values encountered in the recycled mixtures range from 2704.5 MPa (0.39 x 10^6 psi) to 8507.2 MPa (1.23 x 10^6 psi) for 1 to 7 day room curing, which is considered as normal limits observed in field for newly constructed asphaltic concrete and sulphur-asphalt pavements (38, 43, 44). Resilient modulus of field cores

Table 4.1 : Resilient Modulus Test Results

Test Series	Resilient Modulus* Values: 1 Day Room Curing	7 Day Room Curing	7 Day Heat Soaking
MSA	5.49 (0.797)	8.40 (1.218)	12.17 (1.766)
ESA	6.10 (0.885)	8.50 (1.233)	11.66 (1.692)
MBA	2.99 (0.434)	3.01 (0.437)	3.20 (0.465)
DTA	2.70 (0.392)	2.80 (0.406)	2.93 (0.424)
VRA	3.65 (0.530)	3.68 (0.533)	5.86 (0.850)

* MPA x 1000 (psi x 10^6)

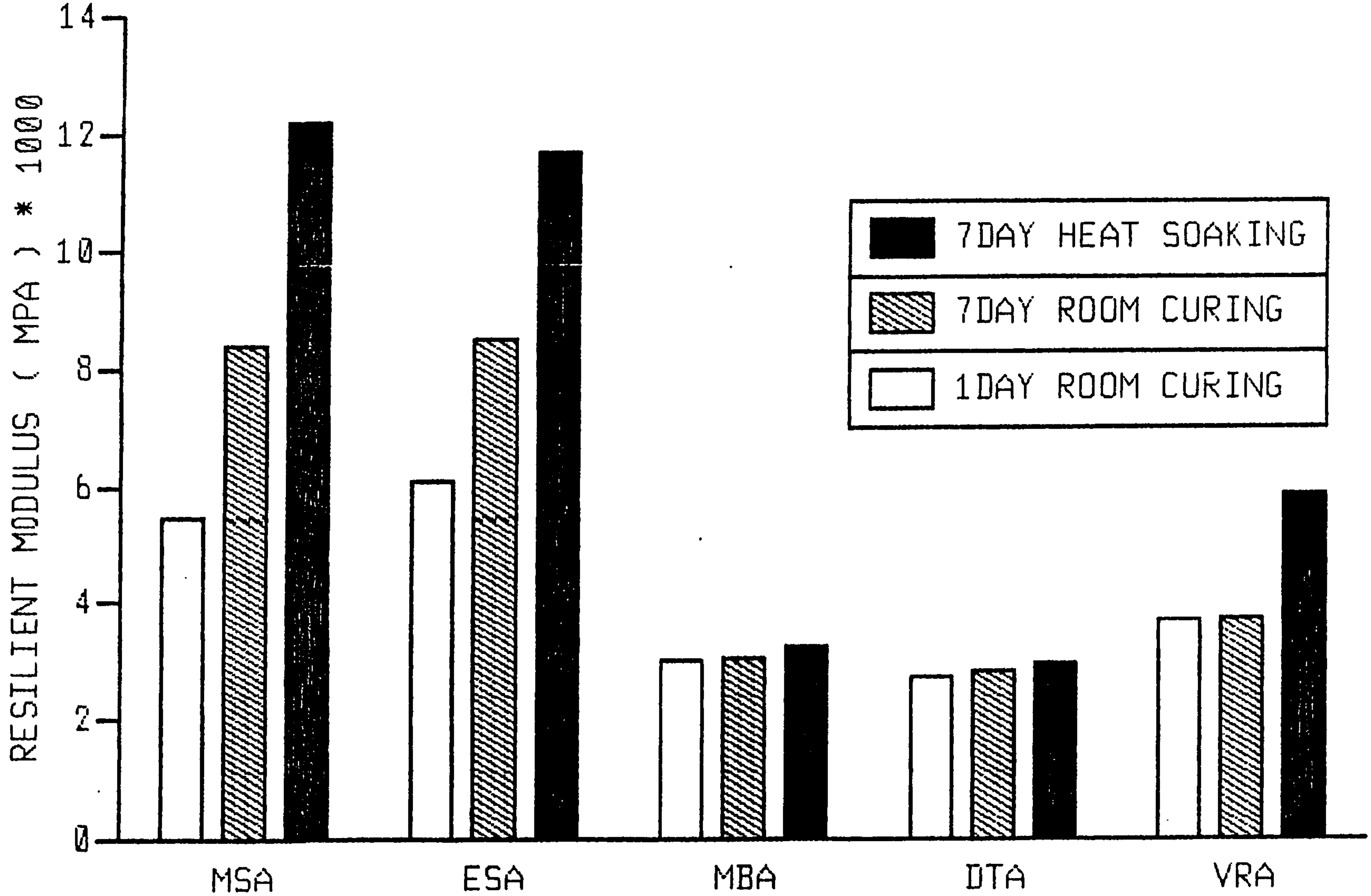


Fig. 4.4 : Resilient Modulus Test Results

extracted from 48 months aged sulphur-asphalt test road on US Highway 69 was reported by Gallaway et al (45) to be 8100 MPa (1.17 x 10^6 psi) which is close to 12,000 MPa (1.74 x 10^6 psi) value observed here in sulphur based recycled mixtures subjected to 7 day conditioning at 60°C. Somewhat higher values of the above order are expected in this research as compared to the western region since stiffer asphalt binder of 60/70 pen is used for this climate as against 80/100 or even softer grade being used in the west.

Asphalt being thermoplastic material, resilient modulus of asphalt concrete depends upon its temperature. Since asphalt pavement layer undergoes cyclic changes in temperature due to daily and seasonal climatic variation, study of the effect of temperature on resilient modulus values will be useful. This was carried out for 4 test temperatures, viz. 25°C (77°F), 40°C (104°F), 50°C (122°F) and 60°C (140°F). The results are summarized in Fig. 4.5.

Throughout the range of temperatures studied, the moduli values of sulphur recycled mixtures are higher than MBA, DTA, and the control mix VRA. The MBA and DTA showed somewhat lower resilient modulus at 25°C (77°F) in comparison to VRA (by 18.05 and 26.1 percent, respectively), but at higher temperature of 60°C (140°F) all the three mixtures showed nearly the same moduli values. At this temperature the MSA and ESA showed 296.07 and 403.93 percent higher resilient modulus in comparison to the control mix VRA. Higher resilient modulus associated with the use of sulphur should be advantageous for the hot region of the Arab World where rutting under wheel track could

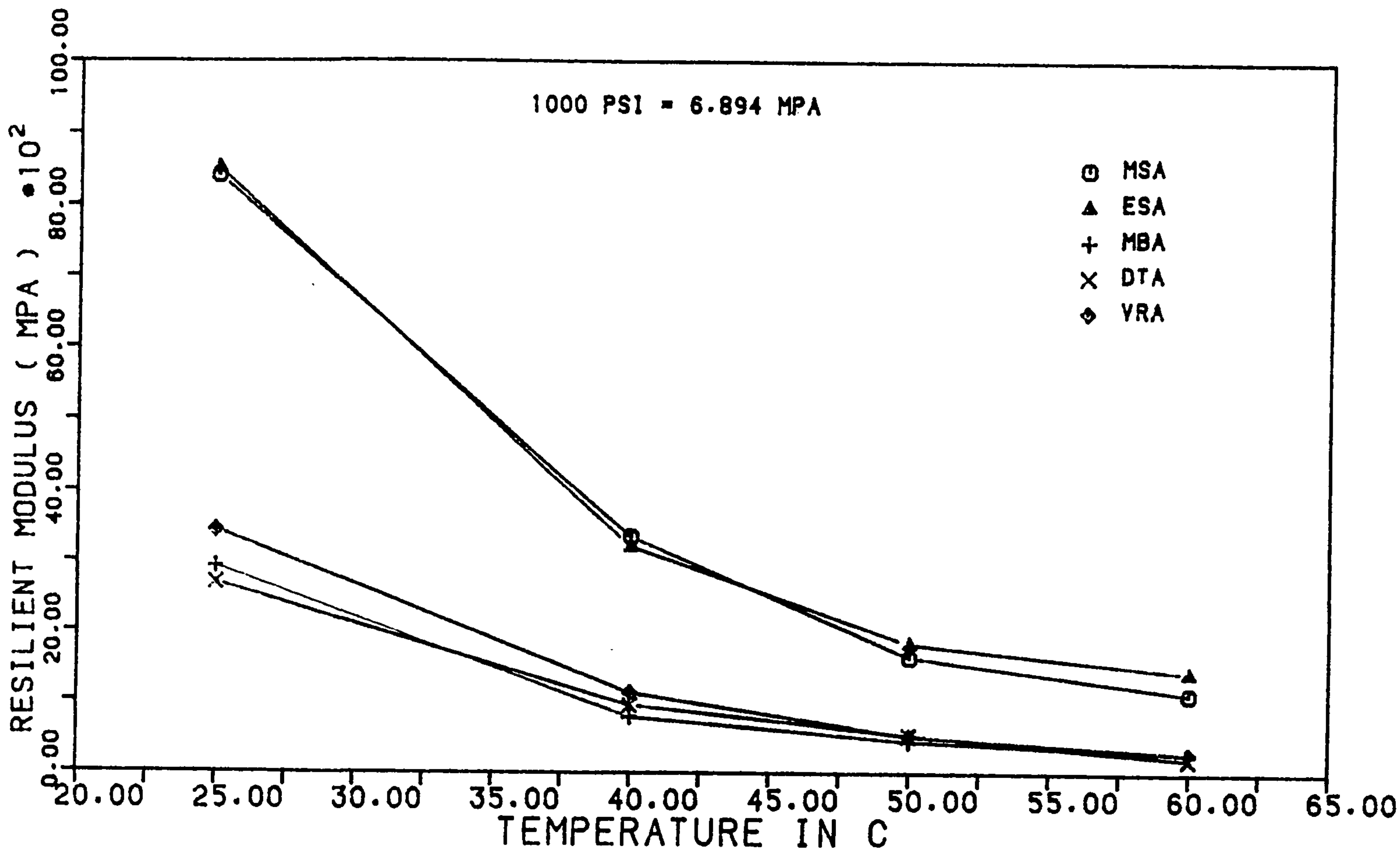


Fig. 4.5 : Effect of Temperature on Resilient Modulus

be a serious problem in pavement performance.

4.4 Split Tensile Strength

The Marshall briquettes, which were tested for resilient modulus after being cured as specified, were finally failed in the indirect tensile test after completing the resilient modulus test series. The test involved loading the specimen with a compressive load acting parallel to and along the vertical diametral plane through 0.5 in. (13 mm) wide stainless steel strips which are curved at the interface with the specimen. Specimen failed by splitting along the vertical diameter. Split tensile strength is given by the following equation for Marshall briquettes (42)

$$\text{Tensile strength, kPa} = 6140\ P_f/h \qquad \text{Eq. 4.3}$$

where P_f is the total load at failure in kN and h is the sample thickness in mm. The strain rate of 50.8 mm (2 in.) per minute was used in the test because it could be easily performed on the Marshall testing machine. The tests were conducted at room temperature at 22.2 - 23.3°C (72 - 74°F).

The results of split tensile strength test are summarized in Table 4.2 and also shown by bar charts in Figure 4.6. It is observed from the above table and figure that split tensile strength of various mixtures under different curing conditions follows the same general trend as that of the resilient modulus. Sulphur recycled mixtures, both MSA and ESA, show significant increase in 7 day room cure and 7 day heat soak, i.e. on average by 42.77 and 67.16 percent, respectively, above

Table 4.2 : Split Tensile Strength Test Results

Test Series	Split Tensile Strength MPa (psi) 1 Day Room Curing	7 Day Room Curing	7 Day Heat Soaking
MSA	1.03672 (150.36)	1.45599 (211.78)	1.80250 (261.43)
ESA	1.08753 (157.73)	1.57294 (228.14)	1.74852 (253.60)
MBA	1.01473 (147.17)	1.12041 (162.50)	1.37708 (199.73)
DTA	0.97178 (140.94)	1.08546 (157.43)	1.37807 (185.37)
VRA	1.12254 (162.81)	1.19383 (173.15)	1.45098 (210.45)

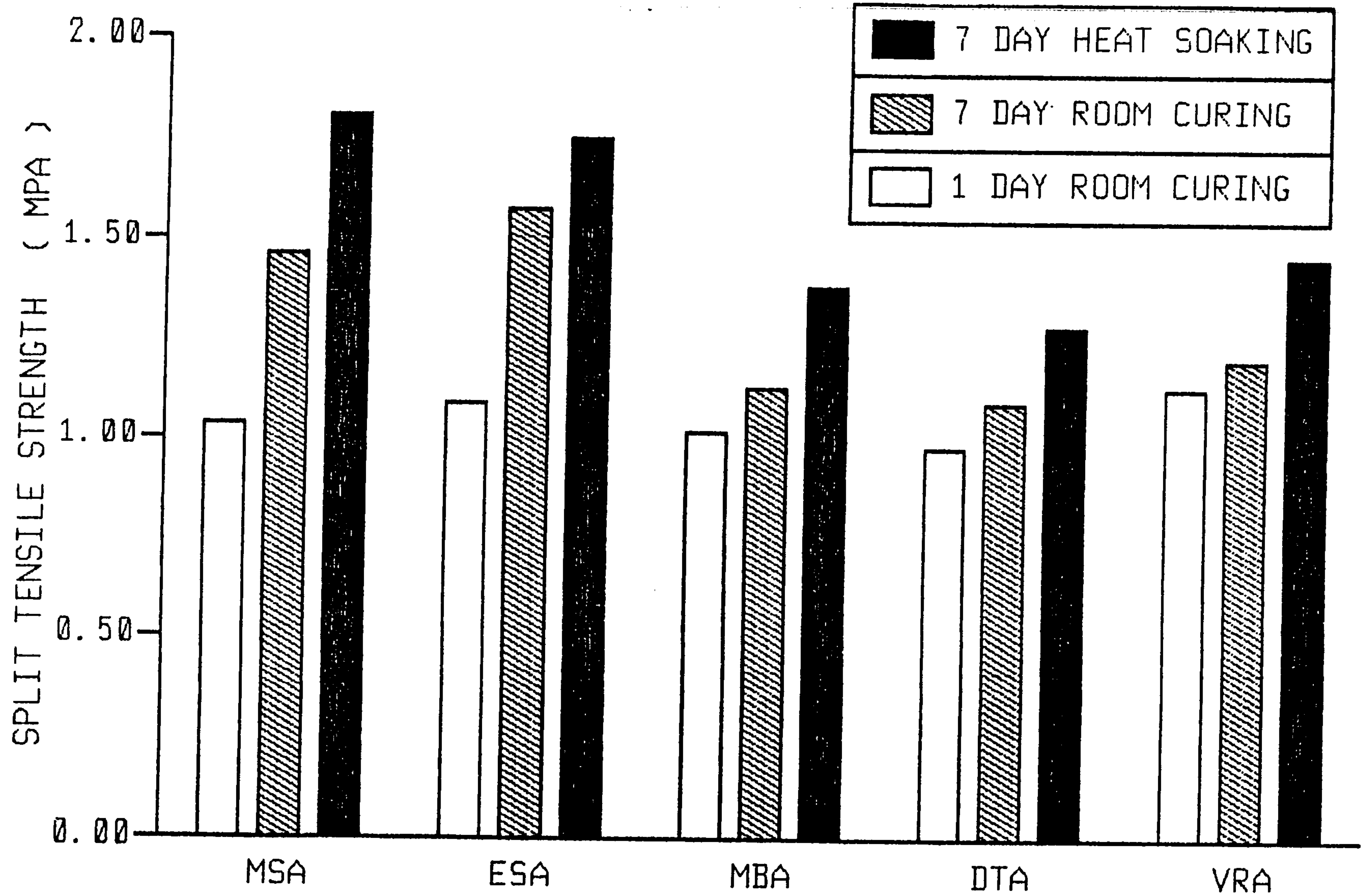


Fig. 4.6 : Split Tensile Strength Test Results

1 day room cure strength. The corresponding values of the other two recycling series, viz. MBA and DTA, on average are found to be 11.04 and 33.66 percent, respectively. The control mix showed increase in tensile strength of the order of 6.35 and 29.26 percent for the above conditions of curing, which is found to match closely with that of MBA and DTA mixes. Comparison of strength values of different mixtures indicates nearly same strength of all mixtures after 1 day room cure; but significantly higher 7 day room cured strength of sulphur recycled mixtures was observed, on average by about 27.02 percent, above that of the control mix. Similarly, comparing 7 day room cured strength of MBA and DTA with that of the control mix, it is observed that the above mixtures have strength values 0.94 and 0.91 times that of the VRA. Strength after 7 day accelerated conditioning for MSA and ESA series is found to be, on average, 22.37 percent above that of the control mix. The MBA and DTA series showed lower tensile strength, by about 8.5 percent, below that of the control mix. The 7 day room cured strength ranges from 1085.46 to 1572.94 KPa (157.43 to 228.14 psi) which shows normal range encountered for bituminous pavements.

4.5 Fatigue Testing

As defined by Yoder and Witczak (46) fatigue is the phenomena of repetitive load induced cracking due to a repeated stress or strain level below the ultimate strength of the material. Since most pavement materials fail in tension, the tensile characteristics of the materials and the behavior under repeated tensile stresses or strains are critical.

Several types of tests employing different methods have been used to study the fatigue behavior. Researchers have developed test methods using beam shaped specimens, direct tension and compression axial load fatigue tests, and repeated load indirect tensile tests (46).

This research makes use of the indirect tensile test, also known as diametral test, to study the fatigue behavior. Test equipment described in section 4.2 was used to apply the repeated loading. Test was conducted at 40°C (104°F) to simulate average temperature of the pavement under inservice conditions. Initial elastic tensile strain levels in the range of 75 to 250 microns were applied and held constant till fracture occurred. The corresponding loads were computed from the Eq. 4.2. In all cases mode of failure was instantaneous due to crack development along the diameter in the vertical plane. To enable the machine to stop automatically at the point of failure of the specimen, a foil tape was attached to the specimen to connect it to the control panel so that the loading system could be dis-engaged and the machine stopped automatically as soon as the foil was broken consequent to the failure of the specimen (41). The number of load repetitions to failure for the given initial tensile strain applied was recorded in each case. The results of various test series are plotted in Figs. 4.7 to 4.11. Fig. 4.12 summarizes results of each test series and compares them together. Response of each recycled mixture was found to be similar to that of the virgin control mixture.

A linear relationship was obtained between the logarithm of initial tensile strain and the logarithm of fatigue life and can be expressed by

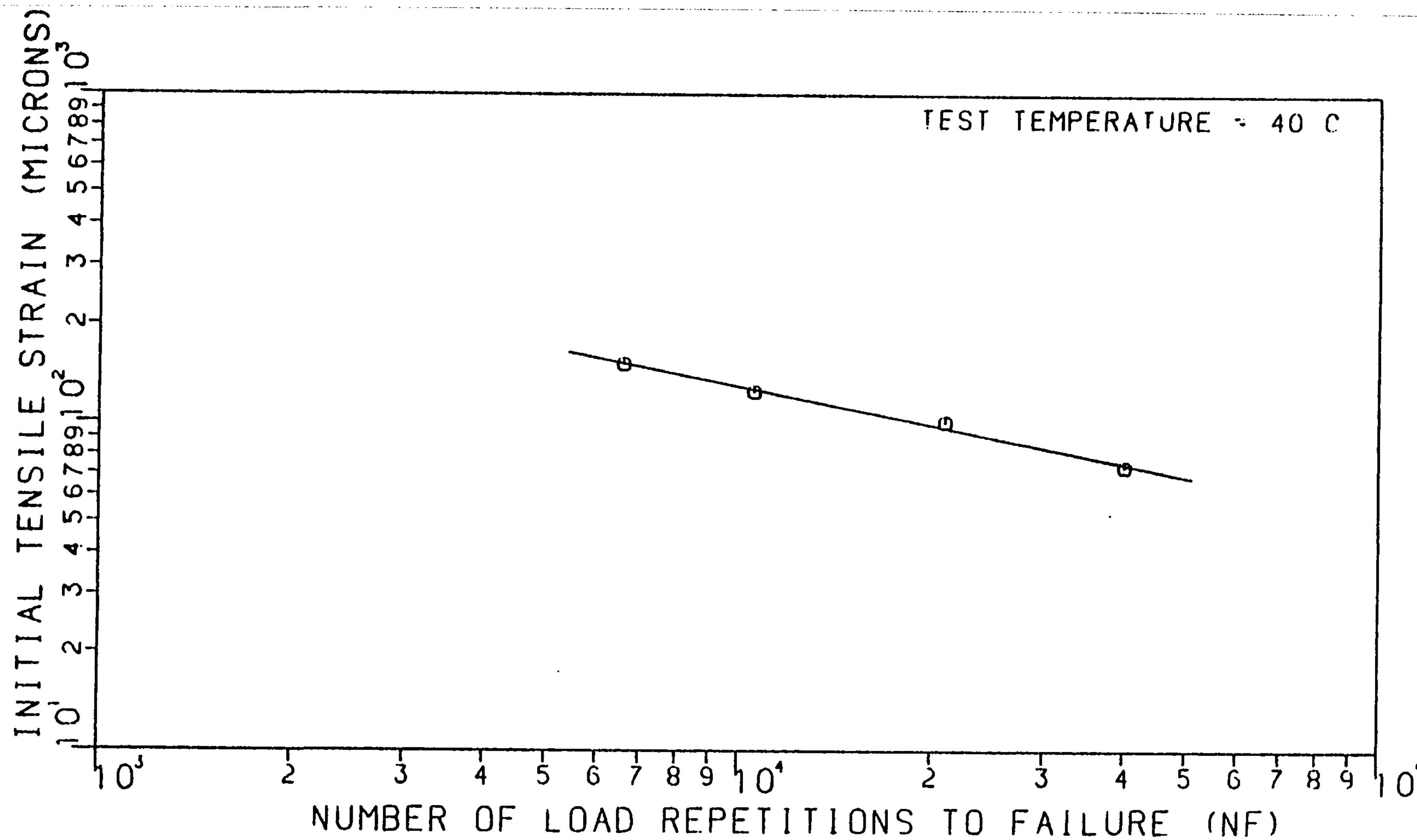


Fig. 4.7: Fatigue Life for MSA Mix.

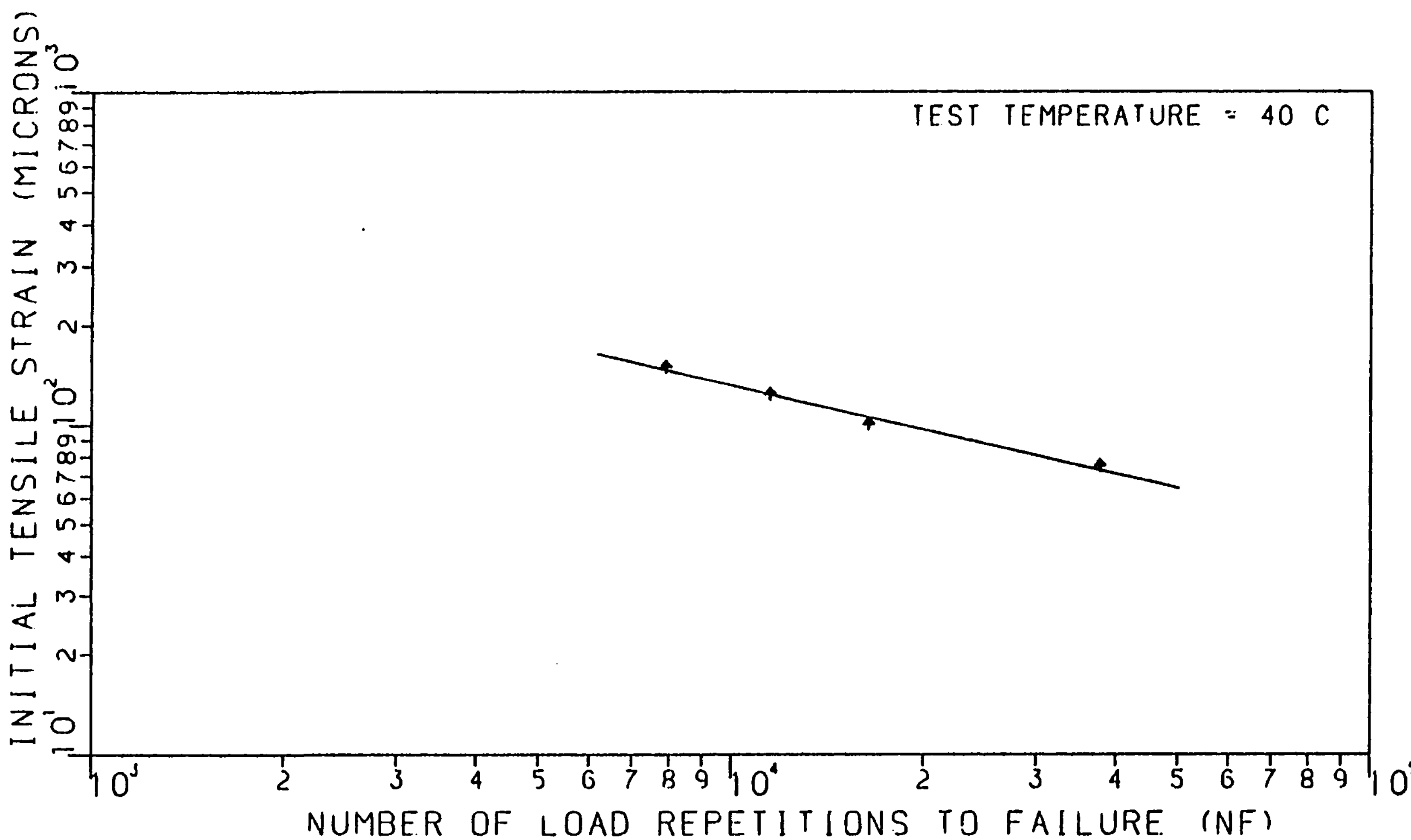


Fig. 4.8: Fatigue Life for ESA Mix.

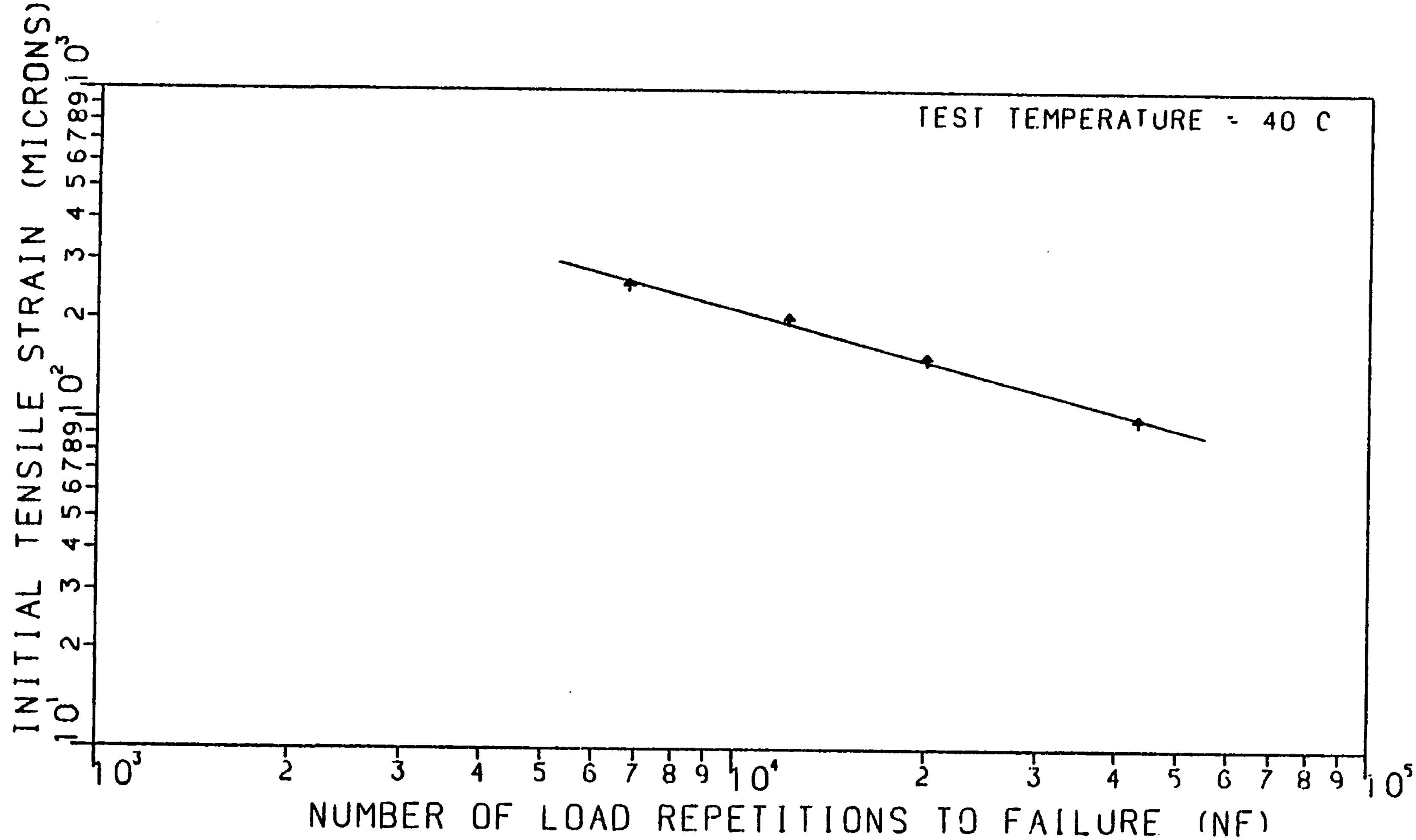


Fig. 4.9: Fatigue Life for MBA Mix.

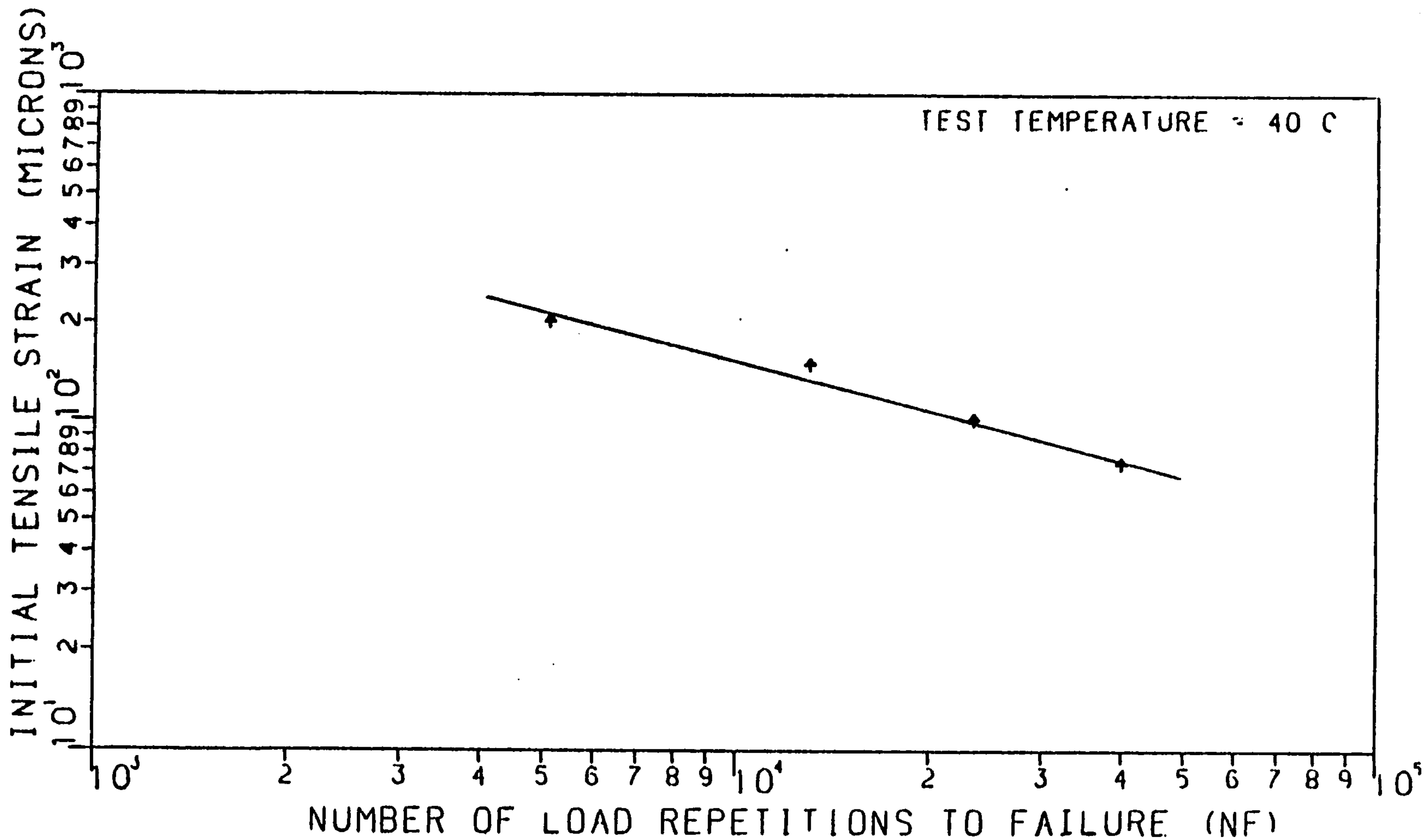


Fig. 4.10: Fatigue Life for DTA Mix.

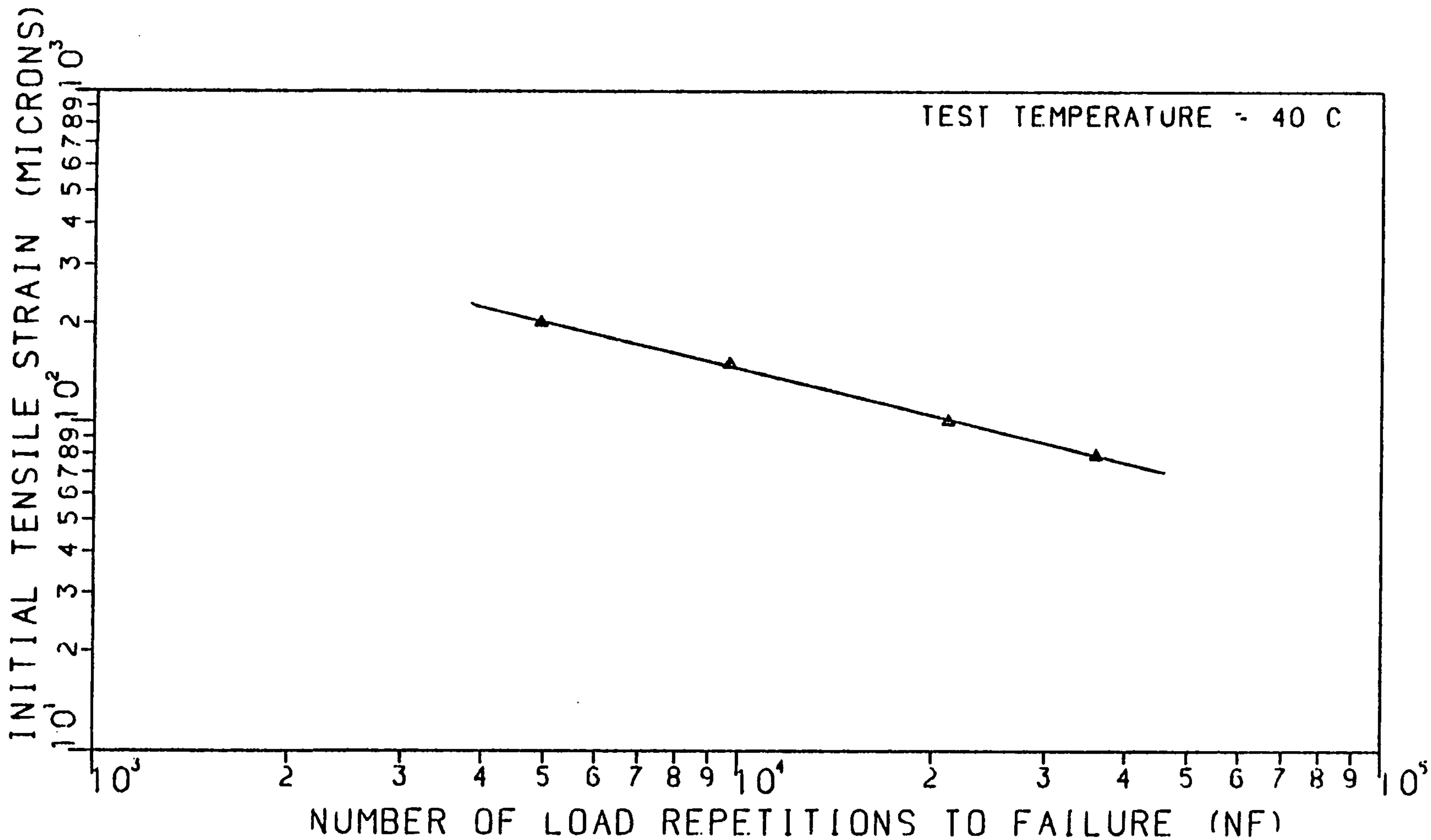


Fig. 4.11: Fatigue Life for VRA Mix.

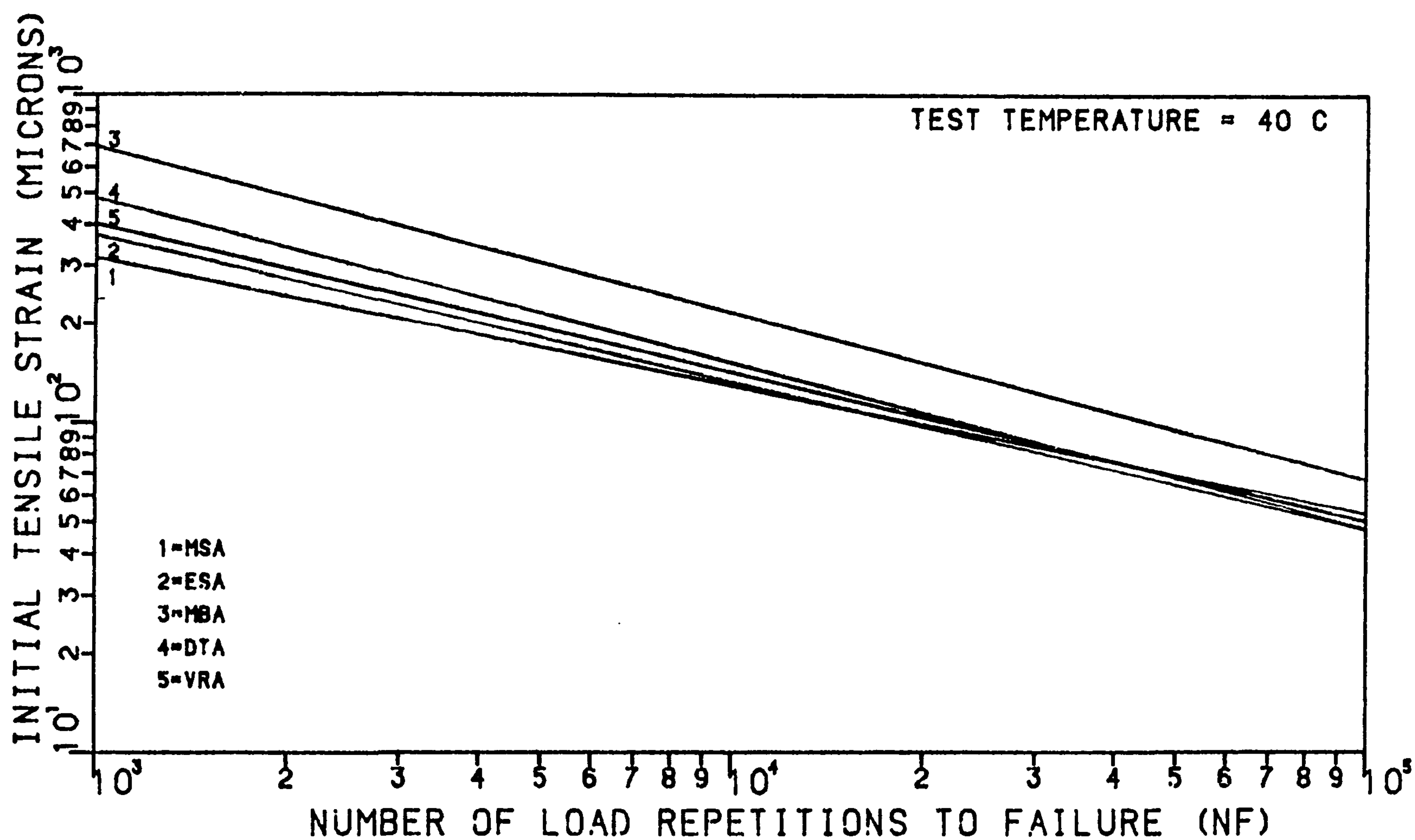


Fig. 4.12: Comparison of Fatigue Lives of Various Mixtures.

the following equation.

$$N_f = a(1/\varepsilon_t)^b \qquad \text{Eq. 4.4}$$

where

N_f = fatigue life

ε_t = initial tensile strain

a = antilogarithm of the intercept of the logarithmic relationship

b = slope of the logarithmic relationship between fatigue life and initial tensile strain

Similar relationship is reported by other investigators for both virgin and recycled asphaltic concrete (47). Following observations are made from the fatigue curves shown in Figs. 4.7 to 4.12.

(i) Fatigue life increases with decrease in initial tensile strain applied and follows a linear logarithmic relationship. The regression constants and coefficient of correlation obtained in each case are summarized in Table 4.3. High coefficient of correlation obtained in each case shows high degree of linearity. The values of regression constants depend upon the mixture properties. The range of values obtained here are similar to that reported by Whitcomb (47) for recycled and control mixtures using similar type of test technique. In the above study values of regression constant 'a' range from 5.19×10^{-8} for cyclogen M recycled mix to 6.08×10^{-3} for virgin control mix and the values of regression constant 'b' range from 3.01 for cyclogen M recycled mix to 1.67

Table 4.3 : Regression Constants and Coefficients of Correlation for Various Mixtures in Fatigue Tests

Mix Type	Regression Constants a	b	Coeff. of Correlation R^2
MSA	1.079×10^{-6}	2.562	0.992
ESA	2.266×10^{-5}	2.229	0.984
MBA	6.044×10^{-4}	1.968	0.995
DTA	2.551×10^{-4}	1.988	0.974
VRA	7.709×10^{-5}	2.114	0.995

for virgin control mix (47).

(ii) The slopes of the best-fitting straight lines for recycled mixtures are very similar to the control mix.

(iii) For a given tensile strain applied, say 150 microstrains, the Fig. 4.12 indicates fatigue lives of MSA, ESA, MBA, DTA and VRA mixes to be 6800, 7700, 21000, 10200, and 9300 load repetitions respectively. Different fatigue lives obtained for a common initial tensile strain applied should consider the fact that resilient modulus values of the individual mixtures were also different. Considering from constant stress application point of view corresponding to 150 microstrains for the control mix, the tensile stress applied works out to be 168.57 kPa (150×10^{-6} X Resilient Modulus at 40°C). Applying resilient moduli values to the above stress level and working backwards, the strains work out to be 50.33, 52.50, 216.17, and 178.20 microstrains for MSA, ESA, MBA and DTA mixtures, respectively. Applying above values to Eq. 4.4 and Table 4.3, the corresponding fatigue lives work out to be 9900, 7200, 78,600 and 111,500 respectively. This analysis should be considered as approximate since resilient modulus values were determined at 100 microstrains and they are assumed to remain same at 150 microstrains. Thus, sulphur based recycling mixtures show remarkably higher fatigue resistance under equal stress condition, in comparison to the other recycling mixtures including the control mix. How this is going to perform in field under actual traffic and climatic conditions can be answered only from observation of fatigue failure of fullscale test sections subjected to real life traffic. In actual condition in field, the fatigue failure may be under constant strain conditions while the test equipment applies repetitions at constant stress level.

4.6 Vertical Permanent Deformation

Permanent deformation or rutting under repeated application of heavy axle loads is a typical load-associated distress commonly encountered in a hot arid region of the Arab world. In this study vertical permanent strains were recorded during the fatigue test as a function of number of load repetitions. Measurements were made with a precise dial gauge (L.C. = 0.0001 in.) at frequent intervals ranging from less than 100 to more than 10^4 load applications. Measured deformations were converted into vertical permanent compressive strains using the following formula simplified for Marshall briquettes and S.I. units (42).

$$\varepsilon_p = Y_t[(1.534\mu+4.665)/(.8954-.0156\mu)]\mathrm{X}10^{-3} \qquad \text{Eq. 4.5}$$

where

ε_p = Permanent vertical strain

μ = Poisson's ratio (assumed 0.35)

Y_t = Total permanent vertical deformation, mm

Results of vertical permanent strain versus number of repetitions are plotted in Figs. 4.13 to 4.18. Fig. 4.18 summarizes behavior of various mixtures corresponding to 100 microstrain level (initial tensile

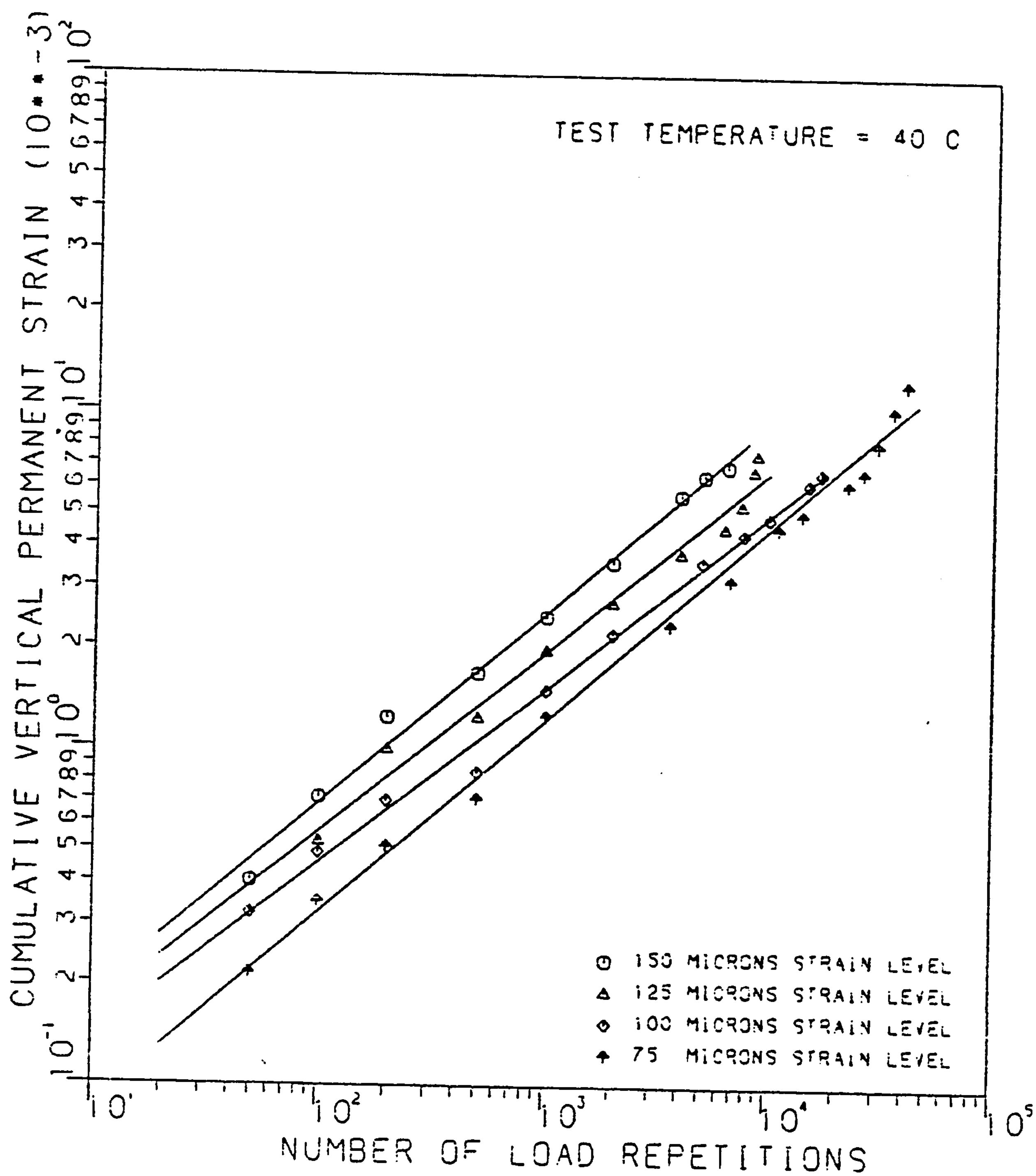


Fig. 4.13: Cumulative Vertical Permanent Strain for MSA Mix.

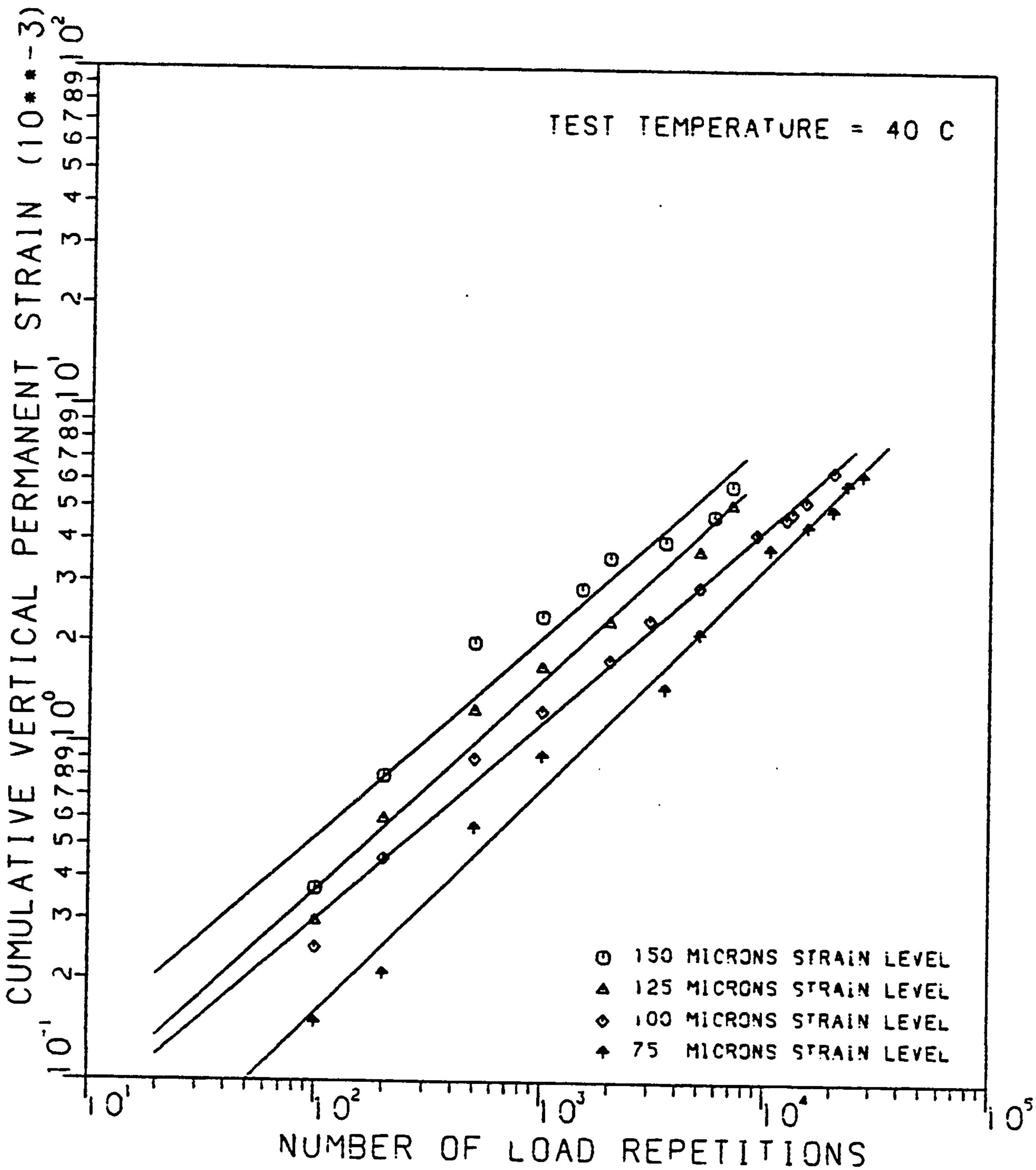


Fig. 4.14: Cumulative Vertical Permanent Strain for ESA Mix.

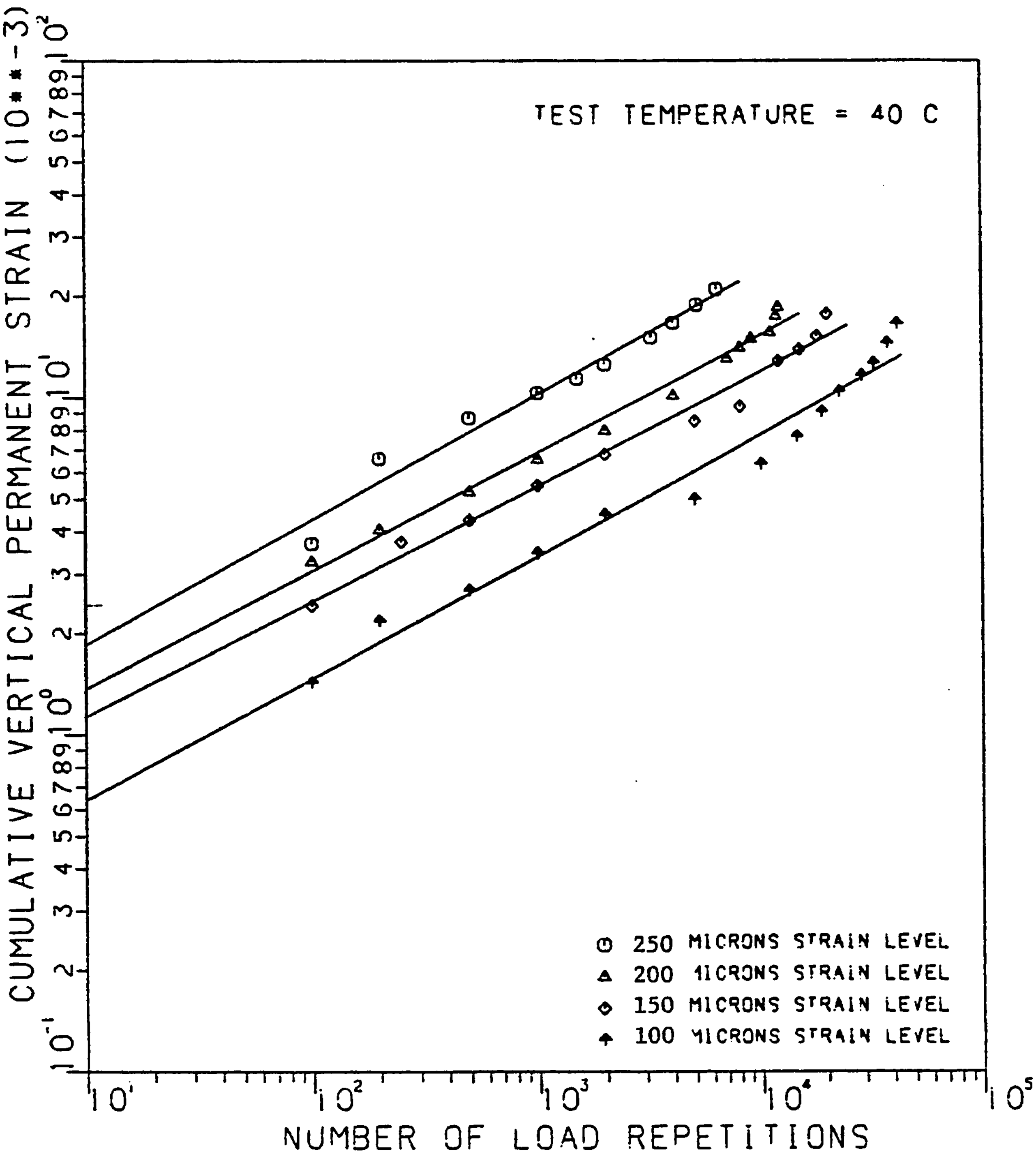


Fig. 4.15: Cumulative Vertical Permanent Strain for MBA Mix.

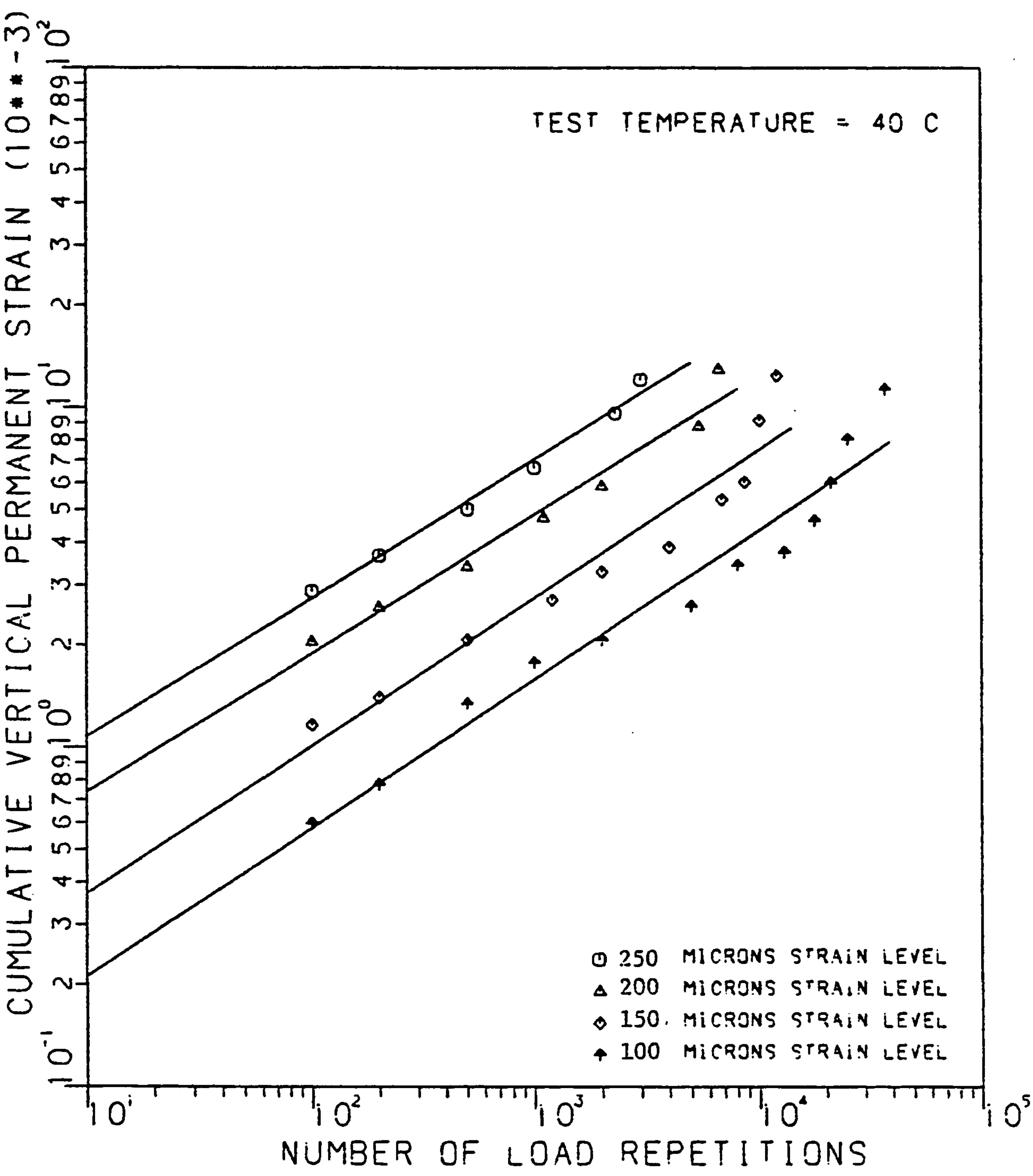


Fig. 4.16: Cumulative Vertical Permanent Strain for DTA Mix.

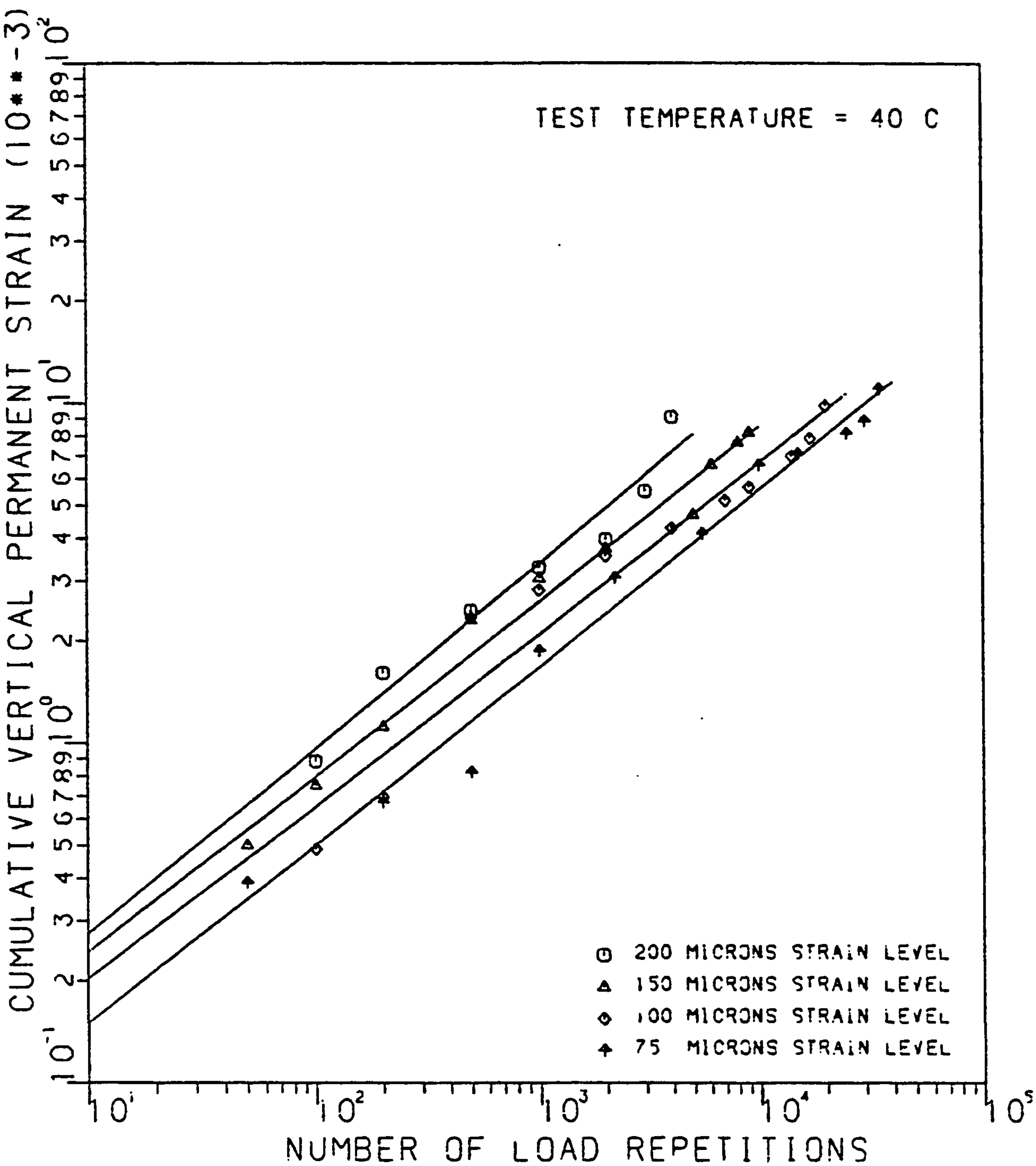


Fig. 4.17: Cumulative Vertical Permanent Strain for VRA Mix.

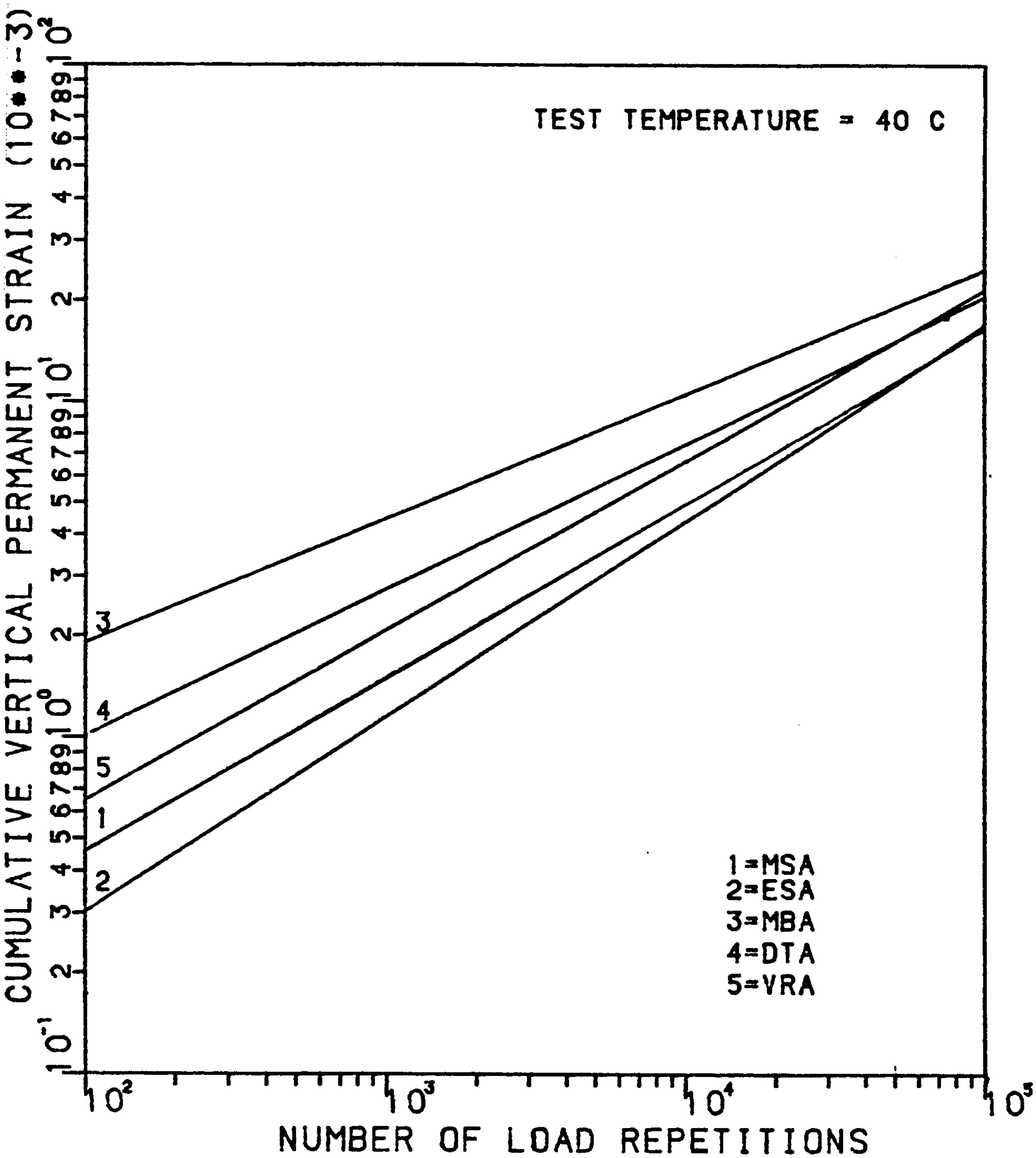


Fig. 4.18 : Cumulative Vertical Permanent Strain for Various Mixtures

strain applied). The specimen tested at higher load, i.e. higher initial tensile strain, show a higher vertical permanent strain than those tested at lower load or lower strains. Majority of research conducted for asphalt concrete has shown that a linear relationship exists between cumulative plastic strain and number of stress applications (46). Similar trend is observed with recycled as well as control mixtures where the permanent strain is seen to accumulate logarithmically with the number of load applications. Regression analysis run on the data points yields the following relationship as also observed by other investigators (47).

$$\varepsilon_p = kN^m \qquad \text{Eq. 4.6}$$

where

ε_p = permanent vertical strain

N = number of stress applications

k, m = experimentally determined constants

The coefficients of correlations and regression constants for each set of curves in Fig. 4.18 are summaried in Table 4.4 which indicates high degree of linearity. Following observations are made from Figs. 4.13 to 4.18.

(i) Permanent strain increases with increase in tensile strain or number of load repetitions applied.

(ii) Sulphur based recycling mixtures show lower rutting susceptibility than virgin control mix for identical test conditions. At 100,000 repetitions, MSA and ESA show same accumulated strain

Table 4.4 : Permanent Deformation Regression Analysis

Mix	Regression Constants		Coeff. of Correlation
Type	k	m	R^2
MSA	4.22×10^{-5}	0.52	0.984
ESA	2.07×10^{-5}	0.58	0.988
MBA	2.77×10^{-4}	0.36	0.972
DTA	1.36×10^{-4}	0.44	0.929
VRA	6.32×10^{-5}	0.51	0.941

which is about 38.46 percent below that of the control mix. The DTA Mixture, at the above level of repetitions, shows almost same plastic strain as the control mix, while the MBA shows about 9.26 percent higher strain than the control mix. Assuming 60 mm as the asphalt layer thickness, the amount of rutting anticipated in the MBA Mix at 100,000 repetitions will be 60 x ε_p i.e. about 1.56 mm which is not significant. The rutting in other mixtures will be still lower.

The above results indicate that the typical failed pavement selected for the study is quite adaptable to recycling. Laboratory tests clearly demonstrate that the recycled mixtures as designed will exhibit adequate resistance to fatigue cracking and rutting in field under actual traffic and environmental setting. These tests strongly support field trials on recycling and performance of test sections to be continually monitored over the design life so that design specifications evolved from the laboratory testing can be suitably refined based on the inservice performance.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

On the basis of literature search and the experiments conducted, following major conclusions are drawn.

1. Due to economic pressure and depletion of good quality mineral aggregate resources, most of the advanced countries worldwide have resorted to recycling of deteriorated asphalt pavements. Technique of pavement recycling has now been developed to an extent that it may prove to be an economic rehabilitation alternative to both overlay as well as reconstruction.
2. Laboratory testing associated with mixture design for recycling projects is necessarily more extensive than that required for typical rehabilitation alternatives such as overlay, reconstruction etc.
3. Extraction tests run on crushed asphalt concrete pavement samples taken from a typical failed segment of Dammam-Abu Hadriyah Expressway, revealed that the reclaimed aggregate had higher percentages of finer fractions. Similarly, the reclaimed asphalt had much higher viscosity, of the order of 20,180 poises at 60°C (140°F), as against 2630 poises of the virgin asphalt. Therefore, virgin aggregate, virgin asphalt and a modifier were needed to correct the mixture deficiencies for recycling.
4. Petroleum based modifiers used in this research, viz. mobilsol

120 and dutrex 729 (UK), followed a linear relationship between logarithm of blend viscosity and percent modifier by weight of total blend. Based on this relationship, percentages of mobilsol and dutrex, to be added to the aged asphalt to lower the blend viscosity to a value equal to that of the virgin asphalt, were obtained as 11 and 12 percent, respectively.

5. Comparison of hardening characteristics of aged asphalt blends, incorporating selected types of modifiers, with that of virgin asphalt revealed slower rate of aging of blends with mobilsol and dutrex. Blend with liquid asphalt (using diesel) showed more rapid aging than that of virgin asphalt and was, therefore, deleted subsequently.

6. Sulphur-asphalt blend in 30/70 weight ratio exhibited higher penetration and lower viscosity (at 60°C) in comparison to virgin asphalt indicating softening effect of sulphur in the binder at least during mixing operation.

7. Mix design by Marshall method yielded optimum binder content of MBA and DTA Mixtures equal to that of the virgin control mixture VRA, i.e. 5.3 percent by weight of total mix. Sulphur recycled mixtures, however, required higher optimum binder content of 6.2 percent which represented volume equivalent of percent asphalt in the VRA mixture.

8. Marshall properties of recycled mixtures were found to be similar to that of virgin control mixture except for significantly higher immersion index (more than 100 percent) encountered with MSA

mixture. The latter behavior may be attributed to some sort of 'gel' formation during 24 hour immersion in water at 60°C caused by the cementing agent used in the modified sulphur.

9. Resilient moduli of recycled mixtures as well as control mixture were found to be in the same general range as of newly constructed virgin asphalt pavements in field. Sulphur recycled mixtures showed significant increase in resilient modulus, by 39.37 to 52.86 percent due to 7 day room curing, and by 91.17 to 121.57 percent due to 7 day heat soaking at 60°C (140°F). This could be attributed to the combined effect of binder stiffening and sulphur recrystallization. Hardening of virgin asphalt due to heat soaking is corroborated by increase in resilient modulus by 60.15 percent when subjected to 7 day heat soaking. Slower aging characteristics of MBA and DTA mixtures were demonstrated by comparatively less significant increase in resilient moduli when subjected to similar conditioning.

10. Splitting tensile strength of recycled and control mixtures exhibited values in the range normally encountered in virgin asphalt mixtures. Effect of accelerated conditioning by heat soaking was similar to what was observed in case of resilient modulus property.

11. Repeated load fatigue cracking and permanent deformation characteristics of recycled mixtures were found to be similar to that of the virgin control mixture, and could be represented by the following models:

$$N_f = a(1/\varepsilon_t)^b \quad \text{for fatigue cracking}$$

$$\varepsilon_p = k(N)^m \quad \text{for vertical permanent deformation}$$

Values of regression constants of the above equations fall in the range reported for virgin asphalt concrete mixtures indicating compatibility of recycled mixtures with that of virgin asphalt concrete in terms of their resistance to fatigue cracking and rutting under repeated applications of traffic loads.

Laboratory results strongly support fullscale trials on recycling in field with a view to monitor performance of recycled pavements under actual traffic and climatic conditions prevailing in the Kingdom. This will also help in better understanding of the long term effects of modifiers in rejuvenation of aged asphalt and may lead to further refinement in laboratory mix design procedure. Life-cycle costs data should also be developed from the performance studies so as to work out the economic viability of recycling process for the conditions prevailing in the Kingdom.

Potential use of modified sulphur for water sensitive aggregates may further be explored as the limited study conducted here has demonstrated no drop in strength (in fact a gain in strength was observed) during 24 hour conditioning in water.

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APPENDIX

Typical Calculations for Weights of Various Constituents for Fabrication of one Marshall Briquette

(A) For ESA with 6.2% binder; 1200 gm aggregate used to prepare one Marshall briquette

Total Mix = 1200x100/(100-6.2) = 1279.3 gm

Total binder required = 79.3 gm

To satisfy the ratio of 50:50 of reclaimed versus virgin aggregate, we need 600 gm of reclaimed aggregate.

Therefore, crushed pavement = [600 / (100-5.8)]x100= 636.9 gm

Hence, reclaimed asphalt = 36.9 gm

The sulphur binder = 79.3 x 30/70 = 34 gm

New asphalt = 79.3 - (34 + 36.9)= 8.4 gm

(B) For MBA with 5.3% binder

1200 gm aggregate used to prepare one Marshall briquette.

Total mix = 1200x100 / (100-5.3) = 1267.2 gm

To get 600 gm of reclaimed aggregate we need RAP

= [600 / (100-5.8)]x100= 636.9 gm

Therefore, reclaimed asphalt = 36.9 gm

Modifier is 11% of total blend.

Therefore, modifer = 36.9 x (11/89) = 4.6 gm

New asphalt = 67.2 - (36.9 + 4.6) = 25.7 gm